

**ACTIVATION MEASUREMENTS
OF NEUTRON-CAPTURE CROSS SECTIONS
IN THE MeV REGION**

Per Andersson

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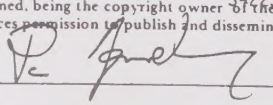
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Abstract Activation measurements in the MeV region are frequently disturbed by accompanying low-energy background neutrons. These neutrons are produced by nonelastic neutron reactions (e.g. (n,n'), (n,np) and $(n,2n)$ reactions) in the irradiated sample and surrounding materials as well as by charged-particle reactions in the target materials. Capture measurements are particularly sensitive, and the contribution to the activation yield may be significant already at 1 - 2 MeV. Experimental techniques for cross-section measurements were developed in which the background influence was minimized by the appropriate choice of target materials and experimental arrangements. The remaining contributions were determined by systematically varying the experimental conditions. The methods were applied to capture cross-section measurements for ^{115}In and ^{197}Au in the neutron energy region 2.0 - 7.7 MeV, and for ^{23}Na, ^{55}Mn, ^{89}Y, ^{127}I, ^{138}Ba, ^{186}W and ^{197}Au at 14.7 MeV. Cross sections for the reactions $^{27}\text{Al}(n,p)^{27}\text{Mg}$, $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ and $^{197}\text{Au}(n,2n)^{198}\text{Au}$ were also measured at 14.9 MeV. Some of the results are compared with statistical model calculations.	
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-Archimedes

1 INTRODUCTION

The neutron and the proton together form the basic constituents of the atomic nucleus. Free neutrons are unstable and must be produced by nuclear reactions, for instance in nuclear reactors, by nuclear weapons or using accelerators. The understanding of the neutron-capture process is of great importance since all free neutrons will eventually either decay into other particles, or will be captured by a nucleus which then subsequently decays by the emission of radiation. Studies of these processes will also give valuable contributions to the description of nuclear structure and to the study of nuclear reaction processes in general.

The first neutron-capture γ -ray experiments [1-5] were performed only a few years after the discovery of the neutron [6] and marked the opening of a whole new branch of experimental research which is still today a very active field. The pioneering work was done by Lea [1] who found the first evidence of γ -radiation emitted after neutron irradiation, by studying the formation of deuterium nuclei when hydrogen was irradiated by neutrons from a Be+Po source. The first actual capture cross-section measurements were performed by Amaldi et al. in 1934 and 1935 [7]. In the following years a number of disco-

veries were made with new measuring techniques, in a large number of laboratories.

The (n,γ) experiments are usually divided into different categories according to the energy range of the neutrons used for the irradiation. One may distinguish the thermal-energy range, the resolved-resonance region, the unresolved-resonance region and the fast-neutron energy range. For each of these regions there are various neutron sources available and different types of detection equipment suitable for the different experiments. Since the work described here is concerned with total-capture cross-section measurements performed with monoenergetic neutrons of an energy above 2 MeV the following discussion will be limited to this type of experiment.

There have been two experimental methods used in capture cross-section measurements with monoenergetic neutrons above 2 MeV. One is the prompt radiation detection method, in which the cross sections are deduced from measurements of the prompt γ rays emitted by the excited nucleus after neutron capture. The other is the activation technique, in which the cross section is obtained by measuring the radiation from the radioactive reaction products.

There are different ways of detecting the prompt γ -ray radiation. Usually one uses a total absorption detector (e.g. a large scintillator) which gives a detector pulse proportional to the sum of

the energies of all the emitted γ rays in the decay of a particular nucleus, or a Ge(Li) spectrometer can be used which gives a pulse which is proportional to the energy of each individual γ ray. Irrespective of the method used, a detector bias is usually required to eliminate the counting of inelastic events. The major difficulty is then to separate the capture events from the background of the inelastic scattering in the part of the γ -ray spectrum which is below the lower-level discriminator. This is done by extrapolation to zero pulse height, thereby introducing an uncertainty in the obtained cross section. This problem becomes worse with increasing neutron energy, and limits the applicability of the method for capture cross-section measurements at higher neutron energies (i.e. typically above 4-5 MeV).

The activation method is very simple in principle. A sample is irradiated with monoenergetic neutrons whereby radioactive nuclei are created. After the irradiation the induced activity is determined by measuring the emitted radiation. If the decay properties of the radioactive nuclei, the irradiation geometry, the irradiation and analysing times, the sample mass, the efficiency of the radiation detector and the neutron flux integrated over the sample are known, then in principle, the cross section can be obtained. The uncertainty is usually below 10% and in some favourable cases as small as only a few percent. Thus, for higher neutron energies and for nuclei with suitable decay properties, the activation method can be considered to be an accurate method for capture cross-section measurements.

Unfortunately however, accompanying low-energy background neutrons in reality make the measurements rather difficult. A major part of the work described in the present thesis has been devoted to the study of such background sources and one of the main points has been to accurately determine their influence on activation measurements.

It is of vital importance to eliminate the influence of background neutrons since only a small fraction of background neutrons can, in some cases, completely invalidate a measurement. This point is best illustrated by an example. Consider the reaction $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$, which has a capture cross section of approximately 2 mb at 7 MeV and 200 mb at 1 MeV. If the background neutrons have an average energy of 1 MeV a simple calculation shows that only a 1% contamination will result in equal contributions to the yield from the background and the primary neutrons at 7 MeV.

The difficulties associated with low-energy background neutrons in activation experiments have been known since the time of the very first cross-section measurements in the MeV region. In an article by Hughes and collaborators [8], describing one of the first more extensive cross-section measurements, it is stated that "as the capture cross section varies as $1/E$, the presence of only a small number of moderated neutrons can vitiate the results". The experiment was performed with unmoderated fission neutrons with an effective energy of 1 MeV, obtained by irradiating a plate of uranium metal in a beam of slow neutrons. The sample to be activated was enclosed in a

thick cadmium cover to prevent significant leakage of thermal neutrons. An identical sample was simultaneously activated with thermal neutrons. The fast-neutron cross section was obtained from the activity ratio, the known thermal cross section and the calculated ratio of fast to slow flux. The (n, γ) cross sections obtained in this experiment for $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ and $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ deviate approximately 15% and 45% respectively, from today's accepted values.

In 1959 Johnsrud et al. [9] studied the energy dependence of fast-neutron activation cross sections. The experiment was performed to measure capture cross sections with monoenergetic neutrons for 24 nuclei in the energy range from 0.15 to 6.2 MeV. The fast-neutron activity was compared with the activity induced by thermal neutrons. The fluxes were compared by a ^{235}U fission counter. Since the energy dependence of the fission cross section and the thermal cross sections were known, the fast-neutron cross sections could be determined. They used what today are standard ways of obtaining monoenergetic neutrons, by using proton- and deuteron-induced nuclear reactions. To obtain the required neutron energies, the projectiles were accelerated with an electrostatic generator. For lower energies the $^7\text{Li}(p, n)^7\text{Be}$ reaction was used. Above 2.4 MeV proton energy (corresponding to a neutron energy of approximately 0.7 MeV) there will be a second group of neutrons thereby making the $^7\text{Li}(p, n)^7\text{Be}$ reaction useless at higher energies. In the energy region 0.6 to 2.5 MeV the neutrons were produced by the $\text{T}(p, n)^3\text{He}$ reaction and in the energy region from 2.6 to 6.2 MeV by the $\text{D}(d, n)^3\text{He}$ reaction. By

adding the $T(d,n)^4\text{He}$ reaction to those used by Johnsrud et al. it is possible to obtain monoenergetic neutrons in the whole energy range up to approximately 30 MeV.

In the paper by Johnsrud the difficulties associated with background neutrons are only briefly mentioned. To reduce the effect of room-scattered neutrons the sample and the fission counter were enclosed by cadmium sheets. The remaining effects were estimated by repeating activations at great distances from the neutron source. No mention whatsoever is made of background neutrons produced by inelastic scattering in the target materials, fission chamber and the sample itself. The resulting cross sections for ^{115}In and ^{197}Au are considerably higher than those from later measurements [10] for neutron energies above 2.5 MeV. It is very likely that the discrepancies are due to contributions to the yield from background neutrons which were not sufficiently accounted for.

In 1967 Menlove and co-workers published an article [10] containing a thorough discussion of different types of background sources present in activation measurements. Cross sections were obtained for four different nuclei in the neutron energy range 1.0 to 19.4 MeV with the same experimental method as that used in the Johnsrud experiment. The background contributions were experimentally determined and the activation yield was corrected to obtain the cross sections. The results for ^{115}In are in excellent agreement with the cross sections presented here for energies below 5 MeV. However, for higher energies

there are large discrepancies indicating that not even in this experiment were corrections properly made for background neutrons. This is confirmed by measurements at 14-15 MeV where the results of Menlove et al. are a factor of six too high in some cases. It is likely that the measurements were spoiled by contributions of background neutrons from scattering in the target beam stop.

About ten years ago it became abundantly clear that there were still severe unresolved difficulties associated with capture cross section measurements with the activation technique. For 14-15 MeV neutrons the discrepancy between the cross-section results of the prompt detection method and the activation method was in some cases as high as a factor of ten, indicating the presence of large systematic errors.

A number of different approaches have been made to eliminate the influence of the low-energy background neutrons in 14-15 MeV activation measurements. It was found that the problems were caused by low-energy neutrons produced in nonelastic processes mainly in the target-head materials. Valkonen and Kantele [11,12], who were the first to experimentally establish the influence of background neutrons on 14-15 MeV measurements, showed that "correct" cross sections could be obtained by proper correction for the background neutrons. Magnusson and Bergqvist [13] developed a target-sample assembly for which the amount of material close to the target-sample region was minimized, thereby significantly reducing the contribution

from scattering in the vicinity of the sample. From the results of these investigations it is clear that by using small samples, thin targets and a close irradiation geometry the contribution to the activation yield from background neutrons can be appreciably reduced. The remaining contribution can be determined by systematically varying the experimental conditions. This point is discussed in detail in section 3. The difficulties connected with low-energy background neutrons in measurements with 14-15 MeV are now well established. The methods developed to eliminate the contributions from background neutrons, have been applied to a number of cases and the discrepancies between the activation results and the results of the prompt detection method are now eliminated, as is shown in the compilation of Wagner and Warhanek [14].

The problems encountered in measurements in the neutron energy range 2-8 MeV are very similar to those met in the 14-15 MeV experiments, with resulting corrections which are of the same magnitude. A more detailed discussion will be presented in section 3. In more recent measurements in this region adequate corrections for background neutrons seem to have been performed. In 1976 Lindner et al. reported on capture cross sections for several nuclei in the neutron energy region 0.12-2.9 MeV [15]. In this experiment some of the background neutron corrections were determined experimentally and some were obtained by the use of Monte Carlo simulation techniques. A more recent measurement of the cross section for the $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ reaction at the neutron energies 5.8, 6.5 and 7.9 MeV has been

reported by Kornilov et al. [16]. The results are in excellent agreement with the cross sections presented here. In 1983 Hussain et al. [17] reported results which show large discrepancies. It seems likely that proper corrections were not applied and that only the background from room-scattered neutrons was considered.

2 PURPOSE OF THE WORK

The ultimate aim of the work presented in this thesis was to obtain experimental methods for the determination of capture cross sections in the MeV region. The activation method was considered to be the most suitable technique available to achieve this, due to its simplicity and accuracy, provided the problems associated with low-energy background neutrons could be handled properly.

A program was set out to investigate in detail the influence of the background neutrons on capture cross-section measurements. Previous studies performed with 14-15 MeV neutrons [13,18] constituted the starting point for these investigations. Considerable effort has been made to both trace and study background sources. Based on the results of the investigations, experimental techniques could be developed where the background influence was reduced to a minimum and where the remaining contribution could be properly accounted for. The methods were applied to capture cross-section measurements in the neutron energy region 2.0-7.7 MeV and at 14.7 MeV.

The thesis is based on the following publications:

- I G. Magnusson, P. Andersson and I. Bergqvist
14.7 MeV NEUTRON CAPTURE CROSS-SECTION MEASUREMENTS WITH
ACTIVATION TECHNIQUE.

Physica Scripta 21(1980)21.

- II P. Andersson, S. Lundberg and G. Magnusson
ABSOLUTE MEASUREMENTS OF SOME NEUTRON ACTIVATION CROSS
SECTIONS IN ^{27}Al , ^{115}In AND ^{197}Au AT 14.9 MeV.

Nuclear Physics Report LUNFD6/(NFFR-3021)/1-22/1978.

- III P. Andersson, R. Zorro and I. Bergqvist
ON NEUTRON CAPTURE CROSS SECTION MEASUREMENTS WITH THE
ACTIVATION TECHNIQUE IN THE MeV REGION.

Nuclear Physics Report LUNFD6/(NFFR-3043)/1-26/(1982).

- IV P. Andersson, R. Zorro and I. Bergqvist
NEUTRON-CAPTURE CROSS-SECTION MEASUREMENTS FOR ^{115}In AND
 ^{197}Au IN THE ENERGY REGION 2.0-7.7 MeV USING THE ACTI-
VATION TECHNIQUE.

Nuclear Physics Report LUNFD6/(NFFR-3055)/1-26/(1985).

Paper IV is a revised version of the LUNFD6/(NFFR-3054)/1-26/(1984) report. The revision consists of a renormalization of the obtained capture cross sections to the ENDF/B-V evaluation of the $^{115}\text{In}(n,n')^{115m}\text{In}$ cross section. A manuscript summarizing the experimental methods presented in papers III and IV has been accepted for publication in Nuclear Instruments and Methods, and a second paper containing the obtained cross sections together with theoretical calculations (see also section 5) has been submitted to Nuclear Physics.

3 LOW-ENERGY NEUTRON BACKGROUND

The experimental situation in most activation experiments is complicated and obscure because of the presence of a number of unidentified or only partly identified sources of background neutrons with various intensities. There are of course specific background problems in each individual experiment. However, some background sources are very difficult to eliminate since they are connected to the basic constituents of most activation experiments. Most notable is the production of background neutrons by nonelastic processes in the irradiated sample and in surrounding materials, denoted background of secondary neutrons. A second important type of background, the background of primary neutrons, is generated by the charged particles used in the neutron production.

Background of secondary neutrons.

The contribution from room-scattered neutrons is the best-known effect of the influence of secondary neutrons and in many experiments the only correction which has been considered. The usual way to determine it has been to activate two samples at different distances from the primary neutron source. One sample placed reasonably close to the source and a second sample at a large distance. By assuming the room-scattered neutrons to be uniformly distributed and the primary flux to follow a $1/r^2$ dependence, where r is the target-sample distance, it is possible to obtain the correction. With this procedure one neglects contributions from scattering in the target which then require additional investigations to be determined. This effect has been neglected or underestimated in several previous experiments, especially at 14-15 MeV. It has been common to use water-cooled target arrangements with much material very close to the primary neutron source, resulting in a considerable contribution to the activation yield from scattered neutrons.

The measurements presented in papers I, III and IV show that by increasing the distance to the walls and by reducing the amount of material in the vicinity of the target-sample arrangement the secondary background flux can be reduced significantly. It was found that in addition to the room-scattered neutron flux the remaining contributions to the activation came from neutrons produced in nonelastic processes in the sample itself and the target beam stop.

The contribution from other sources was negligible. The contributions from room-scattered neutrons and the background from the beam stop may generally be determined by measuring the activation yield for different target-sample distances. This is due to the fact that the distance variation of the flux from a source outside the sample, is usually different from the variation of the primary neutron flux (see papers III and IV for a detailed discussion).

The contribution to the activation yield from low-energy neutrons generated by nonelastic processes in the sample itself is one of the most important background sources in the measurements presented here. As mentioned in the introduction this effect was not observed until 1972 [11,12]. Previous measurements, together with the present investigations, show that neutrons scattered in the irradiated sample itself give a contribution which varies approximately linearly with the sample thickness, i.e. it can be obtained by varying the thickness of the sample. Paper I reports on thickness dependencies for a number of nuclei at the neutron energy 14.7 MeV, and Paper IV contains a study of how the dependencies for ^{115}In and ^{197}Au vary with the neutron energy in the region 2-7 MeV.

Thus, by systematically varying the experimental conditions, it is possible to determine the corrections which must be applied to the activation yield to obtain the cross section. For the measurements in the energy region 2-7 MeV (papers III and IV) neither the thickness dependence nor the distance dependence showed any variation with the

primary neutron energy. In fact for a particular target location and a certain sample, the same corrections could be applied in the whole applicable energy range. However, one should note that since the capture cross section decreases, and as the magnitude of the correction is approximately independent of the primary neutron energy the correction will become more important as the energy increases.

Background of primary neutrons.

The $T(d,n)^4\text{He}$ reaction was used for the production of primary neutrons in the 14.7 MeV experiments (papers I and II). Due to the target materials used and the low deuteron energy required (a few hundred keV) the background of primary neutrons was negligible. In the energy region 1-10 MeV the situation is quite different. In the production of monoenergetic neutrons in this region the $T(p,n)^3\text{He}$ and $D(d,n)^3\text{He}$ reactions are frequently used requiring projectiles of much higher energy, typically a few MeV, which may then generate a background of low-energy neutrons from reactions in the neutron source materials, beam collimators etc.

The typical experimental situation is that the background from primary neutrons rises sharply at some critical energy, following the increase in the (p,n) or (d,n) cross section of one of the materials in the target. Only a few hundred keV above this energy the (n, γ)-activation yield from the background will be comparable to the yield induced by the primary neutrons. At still higher energies it will

dominate the activity.

The standard method of determining the contribution to the activation yield from primary background neutrons consists of repeating the irradiations with "empty targets". By an empty target is meant a target which is identical to the target producing the primary neutrons, but without the tritium or the deuterium or with these replaced by ^1H . By defining a signal-to-background ratio as the ratio between the activation yield from the source reaction and the yield from the corresponding empty target, a measure can be made of the background contribution. The useful energy range of a target arrangement is closely related to how accurately this ratio can be determined, since a large uncertainty in the background determination will result in a large uncertainty in the final cross section.

TARGET TYPE	REACTION	BACKING/ BEAM STOP		ABSORPTION LAYER		ENERGY REGION (MeV)
		MATERIAL	THICKN. (mm)	MATERIAL	THICKN. (mg/cm ²)	
SOLID	$T(p,n)$	Al	0.5	Ti(nat)	1.8-2.4	< 4.4
	"	Au	0.2	^{90}Zr	"	< 4.8
	$D(d,n)$	"	"	Zr(nat)	"	2.5-5.4
GAS	"	"	0.45	-	-	2.5-7.7

TABLE 1. Properties and applicable energy range for different target arrangements for the production of monoenergetic neutrons up to 7.7 MeV.

As described in papers III and IV a thorough investigation was made to determine for which energy ranges different target types could be used by measuring the signal-to-background ratio for different primary neutron energies. It was found that the applicability of commercially available targets was rather limited. However by carefully selecting the materials to be adopted in the construction of a set of new solid targets and a deuterium gas target arrangement, the background was reduced to such an extent that it was possible to extend the neutron energy range up to 7.7 MeV. Table I summarizes the various target types and the energy ranges in which they were applicable, requiring the signal-to-background ratio to be better than two or three.

4 CROSS SECTIONS

Capture cross sections have been determined for a number of nuclei at 14.7 MeV and for ^{115}In and ^{197}Au in the energy region 2.0-7.7 MeV. The cross sections were obtained according to the procedures outlined in the previous sections, with the contribution from background neutrons determined by varying the experimental conditions and by the use of empty targets.

Paper I describes experiments performed to obtain (n,γ) cross sections for the nuclei ^{23}Na , ^{55}Mn , ^{89}Y , ^{127}I , ^{138}Ba , ^{186}W and ^{197}Au at 14.7 MeV. The resulting cross sections establish the fact that the

previous systematic discrepancy between the results of the activation technique and the prompt detection method has been eliminated as a consequence of proper correction for secondary neutrons.

Capture cross sections for ^{115}In and ^{197}Au in the energy region 2.0 to 7.7 MeV are presented in papers III and IV. This is an energy region where there are very few measurements reported and those reported often show large deviations [9-10,15-17,19-25]. For higher energies the most reliable results for ^{115}In have been those of Menlove, but even in this case it is likely that insufficient corrections were made for background neutrons. At approximately 6 MeV the cross section given by Menlove is nearly 50% higher than the present result while the results reported recently by Kornilov et al. [16], are in excellent agreement with the results presented here. For ^{197}Au the situation is similar. Above 4.5 MeV there are only the measurements by Johnsrud [9], which are a factor of 1.5-2 too high, probably due to uncorrected contributions from background neutrons. The results of the most recent prompt detection measurements are in reasonably good agreement with our results [19,20].

The purpose of the experiments described in paper II was to measure some of the cross sections utilized as reference cross sections in this thesis relative to a standard cross section known with high accuracy. By using a proton recoil telescope for the neutron flux determination it was possible to relate the measurements to the n-p scattering cross section which is known to an accuracy of a few

percent. All the reactions are threshold reactions and the activation yield is therefore insensitive to the low-energy background. The obtained cross-section results agree well with other measurements within the limits of uncertainty.

5 MODEL CALCULATIONS OF CAPTURE CROSS SECTIONS.

This section will be devoted to a comparison of theoretical estimates of cross sections for the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ and $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ reactions with the experimental data. The theoretical cross sections were obtained in collaboration with A. Marcinkowski and M. Herman at the Institute for Nuclear Studies in Warsaw. The calculations are based on the statistical model of the compound nucleus and were performed using the computer code EMPIRE [26]. The calculations are not presented in any of the papers included in this thesis. However, a manuscript describing the calculations and presenting the capture cross-section results obtained in the experiments described in papers III and IV, together with much of the following discussion, has been submitted to Nuclear Physics for publication.

For neutron energies below 5-6 MeV the main contribution to the neutron-capture cross section will be from compound-nucleus processes. The basic assumption of the compound-nucleus model is that the formation and decay of the excited nucleus can be considered to be independent. The energy of the captured neutron will be shared

among the nucleons constituting the target nucleus and the decay of the system will be of a statistical nature. The partial compound cross section, $d\sigma(n, \gamma)$, can then be written

$$d\sigma(n, \gamma) = \sigma_C(E_n) \cdot P(E_\gamma) \quad (1)$$

where $\sigma_C(E_n)$ is the cross section for the formation of a compound state by the capture of a neutron with energy E_n and $P(E_\gamma)$ is the probability that it decays by emission of a γ ray with energy E_γ .

The formation cross section and the decay probability can both be related to the transmission coefficients. The transmission coefficient gives the fraction of the incident flux which penetrates into the potential well of the nucleus and can be calculated by the use of the optical model. By treating the decay of the system as the time reversal of the ingoing channels and by making use of the reciprocity theorem it is also possible to relate the exit channels to transmission coefficients. The formation cross section $\sigma_C(E_n)$, will then be given by

$$\sigma_C(E_n) = \pi \lambda^2 T_n(E_n) \quad (2)$$

with $T_n(E_n)$ being the corresponding transmission coefficient and the probability for the decay of a γ ray with energy E_γ will be

$$P(E_\gamma) = T_\gamma(E_\gamma) / \sum_i T_i(E_i). \quad (3)$$

Here $T_{\gamma}(E_{\gamma})$ is the γ -ray transmission coefficient and $\sum T_{i_1}(E_{i_1})$ is the sum of transmission coefficients for all possible exit channels [27].

Equation (1) gives the partial cross section for formation through one single channel and subsequent γ decay through one exit channel. In actual experimental situations some kind of summing and averaging procedure over all the possible spin states is required. The statistical weights of the channels involved depend on the spin I , of the target and I' , of the residual nuclei and on the angular momentum l , and spin S , of the incident neutron. It is assumed that there is always a sufficient number of compound nuclear states of spin $J=l+j$, available in the region of excitation energy. Here, j represents the channel spin (i.e. $j=S+I$) with corresponding primed symbols for the quantities in the outgoing channels. In all cases the requirement of conservation of parity has to be fulfilled. The expression for the cross section for the capture of a neutron with energy E_n , followed by the emission of a γ ray with energy E_{γ} will be

$$d\sigma(n, \gamma) = \pi \lambda^2 \sum_J \frac{2J+1}{2(2I+1)} \sum_{\mu} T_{\mu}(E_n) \frac{T_{\gamma}(E_{\gamma})}{\sum_{\mu'} T_{\mu'}(E_{i_1})} \quad (4)$$

The sum over μ represents a summation of transmission coefficients $T_{\mu}(E_n)$ for all ingoing channels contributing to the population of compound states of spin J , with the restriction $|J-1| \leq j \leq J+1$ imposed by the requirement of angular momentum conservation.

To be able to calculate the capture cross section according to equation (4) all the levels and transmission coefficients have to be known. For most nuclei information on the level properties is rather limited. Usually, only the spins of levels up to a few MeV in excitation energy are well established. For higher energies one assumes that the levels can be described by a smooth level-density function $\rho(\epsilon)$, which is a function of the excitation energy and the spin. The cross section for neutron capture followed by emission of a γ ray with energy between E_γ and $E_\gamma + dE_\gamma$ can then be written

$$d\sigma(n, \gamma) = \pi \lambda^2 \sum_J g \sum_\mu T_\mu(E_n) \frac{T_\gamma(E_\gamma) \rho(E_n + B - E_\gamma) dE_\gamma}{\sum_{\mu'} \int T_{\mu'}(E_i) \rho'(E_n + B - E_i) dE_i} \quad (5)$$

where g is the statistical factor $g = (2J+1)/(2I+1)$, and $\rho(E_n + B - E_\gamma)$ is the level density for the compound nucleus after the emission of a γ ray of energy E_γ and where $\rho'(E_n + B - E_i)$ is the level density for the residual nucleus after decay through channel i , and finally, where B represents the binding energy of the captured neutron. The decays through channels leading to discrete low-lying levels which are known, are treated as separate terms (i.e. with $\rho(\epsilon)=1$). The total neutron-capture cross section is obtained as the integral of $d\sigma(n, \gamma)$ for all possible decays of the compound system through γ -ray cascades, excluding all decays which contain particle emission.

The two main sources of uncertainty involved in the calculations, are those associated with the γ -ray transmission coefficients and the

level-density function. The γ -ray transmission coefficient for electric dipole radiation can be related to the experimental photo-absorption cross section through the relation [28]

$$T_{\gamma} \sim \sigma_{\gamma}(E_{\gamma}) E_{\gamma}^2 \quad (6)$$

where $\sigma_{\gamma}(E_{\gamma})$ is the average photo-absorption cross section of a nucleus at the excitation energy E_{γ} . This cross section can be well described by a Lorentzian line shape at higher energies (i.e. in the giant resonance region). In many cases however, this description fails at lower energies, and since there is very little experimental information available in this region it will result in large uncertainties in the γ -ray transmission coefficients. The Gilbert-Cameron method [29] is commonly adopted for the estimate of the level densities. The parameters needed must, in most cases, be taken from overall systematics since they are usually not experimentally known.

Figure 1 shows the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ and the $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ reaction cross sections in the neutron energy range 2.0-7.7 MeV together with calculated cross sections (solid lines). The calculations were performed according to the formalism outlined above. Only the γ -ray and neutron decay channels were assumed to contribute to the total decay probability since the cross section for decays through other exit channels can be considered negligible in this neutron energy region. In the indium case it is particularly important to follow in detail the γ decay of the compound nucleus through the cascades,

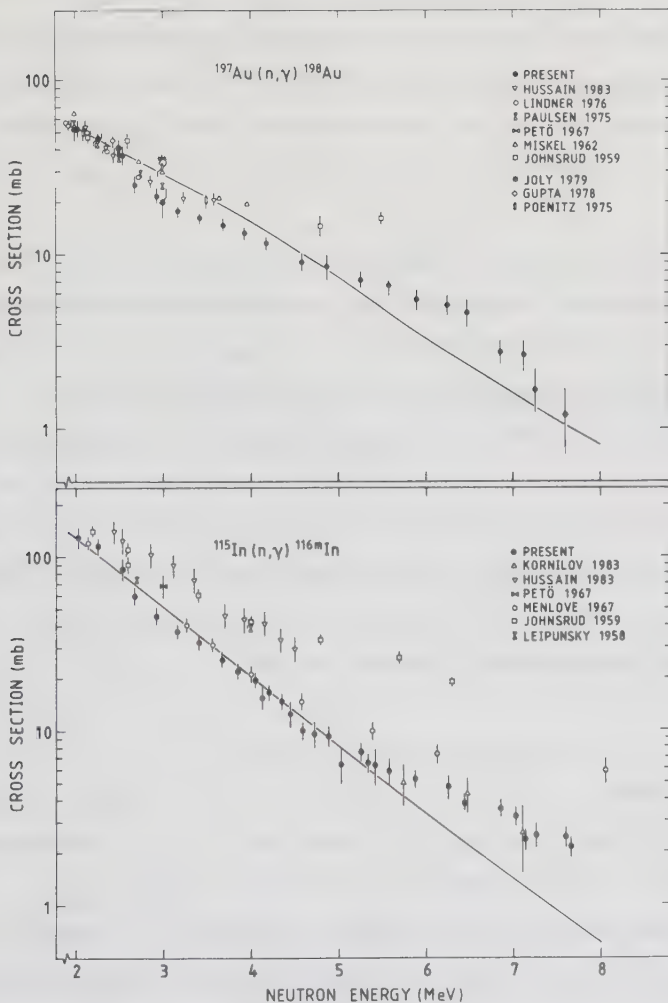


Figure 1. Present cross sections for the $^{115}\text{In}(n,\gamma)^{116m}\text{In}$ and the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reactions together with previous measurements. The solid lines represent theoretical calculations according to the compound-nucleus model.

since when comparing the calculated cross sections with the experimental data, transitions feeding the isomeric state have to be separated from transitions to the ground state. The Gilbert-Cameron density formula was used in the calculations to describe the level density above the highest known level.

The transmission coefficients were obtained by optical-model calculations, except for the γ -ray transmission coefficients which were derived from experimental photo-absorption cross sections. The level-density parameters for the compound nuclei ^{198}Au and ^{116}In were slightly adjusted from the values given by the overall systematics, to reproduce experimental data at resonance energies, and the level-density parameters for the residual nuclei after neutron emission were adjusted at approximately 2 MeV (where the capture cross section is sensitive to the competitive (n,n') channel) to best reproduce existing experimental cross-section data.

The cross sections obtained in the calculations show reasonably good agreement with the experimental data as can be seen in the figure. The general behaviour of the cross section is well reproduced in the region where the compound-nucleus model is applicable, that is below approximately 6 MeV. At higher energies the theoretical cross sections fall below the experimental values by as much as 40-50% which is outside the estimated limits of uncertainty. Considering the uncertainties in the γ -ray transition coefficients and in the level-density parameters we estimate the compound-nucleus calculations to

yield the correct cross section in the energy region considered to within about 30%. The deviation is probably due to the fact that the compound-nucleus model is no longer applicable at these energies but has to be modified to take into account competing direct- and semi-direct processes.

For gold there is a variation in the shape of the experimental cross section around 3 MeV, which the model fails to describe. The deviation is possibly caused by irregularities in the level density of the residual nucleus, which determines the strength of competing (n,n') reactions. It is possible that the experimentally observed shape of the cross section around 3 MeV is due to groups of levels which are not described by the level-density function. At 1-2 MeV a corresponding step in the cross section for gold appears which is caused by the excitation of the first few levels via (n,n') processes. The levels are known and the cross sections are very well reproduced by the model in this range.

6 CONCLUSIONS

The experiments presented in this thesis show conclusively that capture cross-section measurements with the activation technique are very sensitive to accompanying low-energy background neutrons. This is true not only at 14-15 MeV but also at such low energies as 2-3 MeV. It is also shown that the influence of such neutrons can be

minimized by a proper choice of target materials and irradiation conditions. Furthermore, the remaining contributions can be determined by systematically varying the experimental conditions.

Capture cross sections were determined with the new methods developed. The results of the 14-15 MeV measurements show that there is no longer any reason to suspect systematic differences between the cross sections obtained by the activation method and the prompt detection method. In the neutron energy region 2-8 MeV the capture cross-section results agree reasonably well with the most recent prompt detection measurements [19,20] and with previous activation results for lower neutron energies (i.e. below 2.5 MeV). For higher energies the results differ considerably from previous activation results. It is reasonable to conclude that background neutrons were not properly accounted for in these previous measurements.

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Lund, March 1985

A handwritten signature in dark ink, consisting of a stylized 'P' followed by a cursive 'Andersson'.

Per Andersson

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14.7 MeV Neutron Capture Cross-Section Measurements with Activation Technique

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Abstract

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Activation cross-sections for neutron capture have been measured at an energy of 14.7 ± 0.3 MeV for the nuclei ^{23}Na , ^{55}Mn , ^{89}Y , ^{137}I , ^{138}Ba , ^{186}W and ^{197}Au . The influence of secondary neutrons was studied both experimentally and theoretically. The corrections due to secondary low-energy neutrons were determined by systematically varying the geometrical parameters.

1. Introduction

The experimental results on 14–15 MeV neutron capture comprise a rather extensive set of data which is of importance for our understanding of the nucleon capture mechanism. It was early observed [1] that compound-nucleus processes cannot explain the results except possibly for light nuclei. Numerical estimates for direct reactions [2], in which the nucleon is captured directly into a single-particle orbit and the excess energy radiates away, indicated cross-sections for 14–15 MeV neutron capture one order of magnitude below the experimental values. On the other hand, the semidirect (or collective) model [3, 4] has been quite successful in describing the general features of nucleon capture in the giant dipole resonance region. The model considers the excitation of the dipole state as an intermediate stage in the capture process. According to the model a rather smooth variation with mass number would be expected for the 14–15 MeV neutron capture cross section.

The experimental data consist of activation cross-sections and prompt γ -ray spectra. Particular problems have been encountered in the activation measurements. The problems are related to a contribution of low-energy secondary neutrons. Such neutrons are produced in the sample itself by nuclear reactions like $(n, 2n)$, (n, n') and (n, np) . The production can also be seriously high in the target backing and in other materials in the immediate proximity of the target and the sample. It has previously been noted [5] that even a small contribution ($\sim 1\%$) of secondary neutrons is enough to significantly disturb the activation results. In deformed nuclei, for example, the capture cross-section for the secondary, low-energy neutrons is roughly two orders of magnitude larger than for 14–15 MeV neutrons. Various methods [6–15] have been applied in order to reduce the influence of the secondary neutrons and to correct for the remaining contribution.

In the present work the capture cross-sections have been measured by the activation technique. The neutron irradiations of the samples were made in a scattering chamber to reduce the amount of material around the target and the sample. The

chamber and the target backing are made of aluminium which is known to have a relatively low yield of secondary neutrons. The corrections for secondary neutrons were determined experimentally. Model calculations were also performed to estimate the influence of neutrons produced in the sample itself and the results are compared with the measurements.

2. Experimental arrangement and procedure

In order to minimize the influence of secondary neutrons on the (n, γ) activation yield, the neutron irradiations were performed in a vacuum chamber. With this arrangement the amount of material around the target and the sample can be kept small. The details of the set-up have been described in a previous report [9].

The neutrons were produced by the reaction $T(d, n)^4\text{He}$ with the deuterons accelerated to about 360 keV by a 500 kV VdG accelerator. The target was tritiated titanium, 1.4 mg cm^{-2} thick, on a 0.02 mm thick aluminium backing. The average neutron energy was 14.7 ± 0.3 MeV and the energy spread was calculated [16] from the irradiation geometry.

In early experiments, the target backings were prepared from other materials (e.g., copper, gold, tungsten, platinum) and were rather thick, typically more than an order of magnitude thicker than in the present experiment. In those cases, the target backing was one of the main sources of secondary neutrons. It has been observed [9] that the contribution is negligible from the backing used in the present experiment.

In the close target-sample geometries, that were used in order to diminish the influence of secondary neutrons, it is important to keep the size of the beam spot small. Generally it was possible to focus the beam to a 2 mm diameters spot.

The influence of the secondary neutrons was studied by varying the geometrical parameters. For each element a set of irradiations was performed with different sample thicknesses. Another set of measurements was made in which the target-to-sample distance and the sample diameter were varied at the same time. The samples subtended approximately the same solid angle viewed from the target. The distances were varied within the range 0.5–7 mm and the sample diameters within 3–10 mm. The procedure will be discussed in Section 3.

The sample materials are summarized in Table I. The metallic samples (Al, W and Au) were prepared as disks. The powder samples Mn, Y_2O_3 , KCl and BaCl_2 were encased in cylinders made of thin aluminium foils. The sample was mounted on a thin rod together with an aluminium disk (0.1–0.3 mm thick and of the same diameter as the sample) which provided the reference reaction for the (n, γ) activation measurements. Since the activity from $^{23}\text{Na}(n, \gamma)^{24}\text{Na}$ reactions is the same as from the reference reaction $^{27}\text{Al}(n, \alpha)^{24}\text{Na}$ we

Table I. Decay and sample properties required for the cross-section determination

Reaction	Sample				Decay-data		
	Material	Purity %	Abundance % [46]	Energy (keV)	Half-life	Intensity ^{a)} %	Ref.
²³ Na(<i>n</i> , γ) ²⁴ Na	Na I	99.95	100	1368.5 2573.9	15.02 h 15.02 h	100 100	[38]
²⁷ Al(<i>n</i> , α) ²⁴ Na	Al	99.95	100	1368.5	15.02 h	100	[38]
⁵⁵ Mn(<i>n</i> , γ) ⁵⁶ Mn	Mn	99.97	100	846.8 1810.7	2.579 h	98.7 $\pm$ 0.1 27.2 $\pm$ 0.8	[39]
⁸⁹ Y(<i>n</i> , γ) ^{90m} Y	Y ₂ O ₃	99.95	100	202.5 479.5	3.19 h	97.0 $\pm$ 2.9 90.6 $\pm$ 2.7	[40]
¹²⁷ I(<i>n</i> , γ) ¹²⁸ I	KI	99.995	100	442.9	24.99 m	16 $\pm$ 2	[41]
¹³⁸ Ba(<i>n</i> , γ) ¹³⁹ Ba	BaCl ₂	99.97	71.66	165.9	82.7 m	22 $\pm$ 3	[42]
¹⁸⁶ W(<i>n</i> , γ) ¹⁸⁷ W	W	99.98	28.41	479.5 685.8	23.9 h	25.0 $\pm$ 1.0 29.7 $\pm$ 1.2	[43]
¹⁹⁷ Au(<i>n</i> , γ) ¹⁹⁸ Au	Au	99.97	100	411.8	2.696 d	95.5 $\pm$ 0.1	[44]
¹⁹⁷ Au(<i>n</i> , 2 <i>n</i>) ¹⁹⁶ Au	Au	99.97	100	426.0	6.18 d	6.7 $\pm$ 0.1	[45]

^{a)} Photons per 100 decays of reaction product nuclei.

wrapped the Na I powder sample in a cylinder of silver foil and utilized the reaction ¹⁹⁷Au(*n*, 2*n*)¹⁹⁶Au as a reference.

During the irradiation the neutron flux was monitored by a long counter. It was possible to keep the flux constant within 5%. After each irradiation the γ -rays from the induced activity were measured by a Ge(Li) spectrometer. The γ -ray analysis was generally made separately for the aluminium (or gold) disk and the sample in order to obtain as simple activation γ -ray spectra as possible.

The intensity, *Y*, of a particular γ -ray line in the recorded γ -ray spectrum is related to the activation cross-section, σ , by

$$Y = [\phi_n \cdot N_s \cdot \Omega_s] \cdot \sigma \cdot \epsilon \cdot B \quad (1)$$

where ϕ_n is the incident neutron flux (neutrons/sr.s), N_s the number of sample atoms per cm², Ω_s a solid angle, ϵ the detection efficiency for the γ -ray line and *B*, the build up and decay factor, is a function of the half-life of the activity, the irradiation, cooling and analysing times. The *B* factor further contains the properties of the sample such as abundance and decay branching, which are given in Table I. The expression in the brackets was numerically integrated over the sample considering that the neutron source has a finite size.

The activation cross-sections were determined relative to the cross section for the ²⁷Al(*n*, α)²⁴Na reaction. In a separate experiment [17] we have measured the cross section for this reaction by utilizing a neutron-proton telescope with a (CH₂)_n radiator foil for the neutron flux determination. Our result agrees within the limits of accuracy with the value 112 $\pm$ 5 mb at 14.7 MeV [18], adopted here as the reference cross-section.

Even though ²⁷Al(*n*, α)²⁴Na was adopted as the reference reaction we have also employed other reactions in the studies of the influence of secondary neutrons. The requirements are that the reactions are produced in the sample under investigation and that they are insensitive to the low-energy neutrons. It turns out that (*n*, 2*n*) reactions can be applied for the samples studied in this work except for tungsten for which ¹⁸⁴W(*n*, *p*)¹⁸⁴Ta was used. The advantage is that the uncertainties due to the sample geometry are reduced in the determination of the corrections for secondary neutrons.

Since the (*n*, γ) activation measurements were made relative

to the activity from a reference reaction only the relative efficiency of the Ge(Li) spectrometer had to be known. It was determined by using ²²⁶Ra and ⁷⁵Se γ -ray sources. These sources give appropriate γ -ray lines which well cover the energy range of interest in this work (150 keV–2 MeV). The sources are comparable in size with the samples and were placed in the same fixed position. The absolute efficiency, needed in the estimation of the cascade-summing correction (see below), was obtained by utilizing calibrated radioactive sources.

The activation yield was corrected for γ -ray attenuation in the sample and cascade summing effects. The attenuation correction was calculated with the aid of a Monte-Carlo method [19]. The magnitude of the correction is typically less than 10%. The probability of detecting simultaneously two γ -rays or more in cascade cannot be ignored for short source-to-detector distances. A computer code was constructed based on the formula given in [20]. The correction amounts to about 20% for sodium, yttrium and tungsten, but only a few percent in the other cases where cascades occur.

Strong X-rays follow the electron capture decay of ¹⁹⁶Au, produced in ¹⁹⁷Au(*n*, 2*n*)¹⁹⁶Au reaction. Coincidence summing of these X-rays and γ -rays from ¹⁹⁶Au seriously disturbs the γ -ray line at 411.8 keV from the ¹⁹⁸Au activity induced by neutron capture in ¹⁹⁷Au. In order to suppress the influence of these X-rays a 2 mm thick lead absorber was inserted between the gold sample and the Ge(Li) detector.

The cross-section for the production of the 411.8 keV γ -rays was determined relative to the 426.0 keV γ -ray from ¹⁹⁷Au(*n*, 2*n*)¹⁹⁶Au. The cross-section of the latter was measured relative to the ²⁷Al(*n*, α)²⁴Na in a separate experiment. The result 2.23 $\pm$ 0.15 b is in good agreement with previous measurements [18].

3. Influence of secondary, low energy neutrons

The influence of secondary neutrons can be observed by varying the experimental parameters. Following the procedure outlined in our previous work we measure the activation yield as a function of the target-sample distance and of the sample thickness. The results of the measurements are shown in Figs. 1

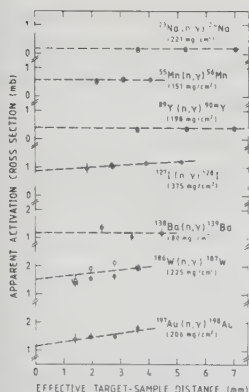


Fig. 1. Dependence of the apparent activation cross-section on the effective distance for measurements performed with constant solid angle subtended by the samples. The experimental dependences are indicated by dashed lines. The thickness values of the used samples are put in parentheses.

and 2, in which the yields are given as apparent cross-sections [6, 9].

Because of the finite sizes of the beam spot and the sample, the apparent cross sections in Fig. 1 have been plotted vs. the effective distance between the target and the sample. The effective distance is defined as the mean value of all possible distances between the beam spot and the sample.

The results (Fig. 1) for ^{127}I , ^{186}W and ^{197}Au indicate a dependence on the target-sample distance. The dependence can be understood in terms of capture of low-energy secondary neutrons produced in material surrounding the target and the sample. The capture cross-sections for low-energy neutrons are high for these nuclei. For the distances used in the present work, the results indicate a linear dependence [9]. The capture cross-sections for ^{23}Na , ^{55}Mn , ^{89}Y and ^{138}Ba are relatively small also at low neutron energies and one should not expect to find any distance dependence for these nuclei.

In the case of gold the effective distance dependence was studied for two different sample thicknesses (206 and 577 mg cm^{-2}). The two curves are almost parallel to each other and the difference between them is due to the increase in thickness. Both sets of measurements have been used in the determination of the cross-section.

The dependence on the sample thickness (Fig. 2) reveals the influence of secondary neutrons produced in the sample itself. The influence is particularly strong for ^{186}W . Also the results for ^{127}I and ^{197}Au indicate some dependence on thickness whereas no dependence was observed for the other nuclei.

The correction for secondary neutrons has been estimated by applying the method previously described [9, 21]. The method is based on a formula [22], which gives the probability, $P_c(\epsilon)$ that a neutron of energy ϵ will make a collision on its way out of the sample. The correction, σ^{sn} , can be expressed by

$$\sigma^{\text{sn}} = \int_E P_c(\epsilon) I(\epsilon) \frac{\sigma_c(\epsilon)}{\sigma_{\text{tot}}(\epsilon)} d\epsilon \quad (2)$$

where $I(\epsilon)$ is the energy distribution of secondary neutrons

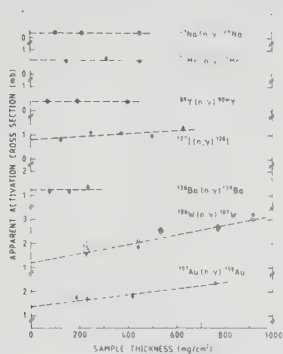


Fig. 2. Dependence of the apparent activation cross-section on the sample thickness. The experimental dependences are indicated by dashed lines. The sample diameters were 5 mm.

produced in the sample, $\sigma_c(\epsilon)$ is the capture cross-section of the isotope considered and $\sigma_{\text{tot}}(\epsilon)$ is the total elemental cross-section (or the weighted total cross-section for composite samples). We estimate $I(\epsilon)$ from the pre-equilibrium and statistical models [23, 24] and normalize the spectrum by the relation

$$\int_E I(\epsilon) d\epsilon = 2\sigma_{n,2n} + \sigma_{n,n'} + \sigma_{n,np} \quad (3)$$

The cross-sections were taken from [18, 25–27]. The results of the calculations of the contribution σ^{sn} , to the apparent cross section for ^{127}I , ^{186}W and ^{197}Au are displayed in Fig. 3. The shaded areas reflect the uncertainties in σ^{sn} due to quoted errors in the cross-section values used in the calculations. Additional uncertainties arise from errors in the estimate of $I(\epsilon)$. The results of the model calculations show generally good agreement with experimental data. However, the data are typically restricted to energies above 2 MeV whereas the most significant contribution to σ^{sn} comes from secondary neutrons with lower energies.

The comparison with the experimental data shows quite good agreement for ^{127}I and ^{197}Au , but it is evident that the σ^{sn} calculations cannot account for the strong thickness dependence observed for ^{186}W . The production of secondary neutrons in a tungsten sample should be about the same as in a gold sample of the same geometry. The total cross-section and the $P_c(\epsilon)$ values are also about the same for the two samples. The capture cross-section of ^{186}W tends, however, to be lower than the ^{197}Au capture cross-section, e.g., at 1 MeV the ratio between the cross sections is near 1:2. This implies that σ^{sn} for ^{186}W is predicted to be roughly a factor of two lower than that for ^{197}Au . The observed dependence, on the other hand, is a factor of two stronger. We do not know the cause of this serious discrepancy. There might be differences in the energy distribution, $I(\epsilon)$, of the secondary neutrons, which are larger than predicted from the pre-equilibrium and statistical model calculations, but we cannot find experimental support for this differences.

The calculations also indicate a dependence on the sample diameter, but the contribution is rather weak. In a previous experiment [9], an attempt was made to investigate the diameter dependence but it was found to be coupled together

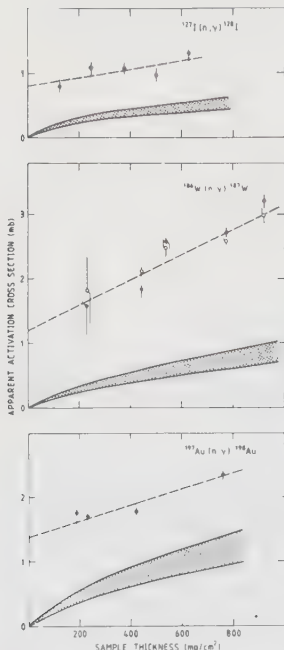


Fig. 3. Dependence of the apparent activation cross-section on the sample thickness. The experimental dependences are indicated by dashed lines and the shaded areas show the contribution of secondary neutrons, σ_{sn} , calculated from eq. (2).

with the distance dependence. A change of the diameter also means a change of the effective distance between the target and the sample. As a consequence, the measurements were performed in which the solid angle subtended by the samples was kept constant. The results reflect the influence of both the distance and the diameter on the apparent cross-section.

We correct for the influence of secondary neutrons by extrapolating the apparent cross-sections to zero effective distance and zero sample thickness. Linear dependencies have been assumed in all cases and least square fits have been made to the experimental points. The uncertainties in the zero intercepts and in the slopes have been calculated from the fits.

The error bars given in Figs. 1–3 represent only the uncertainties due to the statistical counting of the activities. To get the uncertainty in the absolute scale the following sources of error have been taken into account: uncertainties in the determination of the efficiency of the Ge(Li) spectrometer (3–5%), quoted error for the cross section of the reference reaction (4.5%) and uncertainties in the build-up and decay factor. The latter contribution varies from 1–14% depending mainly on the uncertainties in the decay γ -ray intensities (Table I).

4. Results and discussion

The results from the present work are summarized in Table II

together with the results of other experiments. The results of Kantele and Valkonen [6, 7, 29] were obtained from activation measurements utilizing a technique which later was employed by several other groups [8–13] and, in fact, is similar to the procedure used in this work. They succeeded to significantly reduce the influence of secondary neutrons by using an especially designed tritium target head of aluminium. The corrections were determined by studying the dependence of the activation yield on the experimental parameters. A somewhat different approach was made by Schwerer *et al.* [14] who calculated by means of a computer program the flux of secondary neutrons produced in the target head and the sample. The contribution to the activation yield was estimated by assuming an effective energy of 1 MeV for the secondary neutrons.

Capture cross-sections, σ_{int} , derived from the measurements of the prompt γ -ray spectra are also included in Table II. The cross sections represent integration in the spectra of γ -rays to bound levels in the formed nuclei. The activation cross-section, on the other hand, also includes γ -ray cascades through unbound levels. Hence one might expect to find a difference between σ_{int} and σ_{act} . For the comparison we have chosen the data that have been measured by Bundar *et al.* [28]. They have used an arrangement for the γ -ray spectrum measurements which effectively integrates over emission angle. It should be noted that these data agree quite well with other spectrum results, most of which have been obtained with the γ -ray detector positioned at 90° with respect to the particle beam.

Previously, the most serious discrepancy between various experiments was observed for nuclei with large capture cross sections for low-energy secondary neutrons, e.g. ^{127}I , ^{186}W and ^{197}Au . It is evident from Table II that there still are differences greater than the estimated errors even though the worst inconsistencies in the early results have been removed. The present results for ^{127}I and ^{186}W are lower than those obtained by Kantele and Valkonen [6, 29] but the differences are reasonable in view of the uncertainties. For the three nuclei, the results of Schwerer *et al.* [14] are significantly higher than our results. The cause of this disagreement seems to be the influence of secondary neutrons. We note that the corrections, obtained in [14] from numerical estimates of the influence, range from 0.6 to 1.4 mb for these nuclei. We have found that it is difficult to calculate the correction with reasonable accuracy. The difficulty is well illustrated in Fig. 3, which shows the correction for neutrons produced in the sample which is a much simpler calculation than for neutrons produced in surrounding materials. While the model describes quite well the thickness dependences for $^{127}\text{I}(n, \gamma)^{128}\text{I}$ and $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ it fails to reproduce the data for $^{186}\text{W}(n, \gamma)^{187}\text{W}$.

We do not observe any influence of secondary neutrons in the results for ^{23}Na , ^{55}Mn , ^{89}Y and ^{138}Ba . Previous results exhibit rather small differences. In general, the more obvious difference can be attributed to experimental problems of origin other than secondary neutrons. For $^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$ the primary problem is a contribution of the reaction $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ arising from impurities in the sample. The 14.7 MeV cross-section of the (n, p) reaction is 103 ± 6 mb [18] which implies that an impurity of 0.6% (which is not unusual in ordinary Mn material) would give a contribution to the activation yield equal to that from the $^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$ reaction. For $^{138}\text{Ba}(n, \gamma)^{139}\text{Ba}$, there might be problems to accurately measure the intensity of the 166 keV γ -ray line following the β -decay of ^{139}Ba . The absolute

Table II. Comparison of experimental neutron capture cross-section results at 14–15 MeV. Included in the table are previous data for which corrections for low-energy neutrons have been made or for which these corrections are expected to be negligible.

Reaction	Present results (mb)	Other results (mb)		
		Spectrum method [28]	Activation method	Ref.
$^{23}\text{Na}(n, \gamma)^{24}\text{Na}$	0.19 ± 0.03		0.25 ± 0.02 0.24 ± 0.06	Menlove et al. [31] Csikai et al. [32]
$^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$	0.58 ± 0.08	0.78 ± 0.16	0.68 ± 0.07 0.8 ± 0.1 1.4 ± 0.2 0.89 ± 0.08 1.2 ± 0.2 0.76 ± 0.08	Schwerer et al. [14] Vuletin et al. [11] Holub et al. [30] Menlove et al. [31] Csikai et al. [32] Perkin et al. [33]
$^{89}\text{Y}(n, \gamma)^{90}\text{Y}$	0.39 ± 0.04		0.40 ± 0.06 0.50 ± 0.07 1.1 ± 0.6	Schwerer et al. [14] Grench et al. [34] Bramliitt et al. [35]
$^{127}\text{I}(n, \gamma)^{128}\text{I}$	0.62 ± 0.21	0.77 ± 0.16	1.12 ± 0.25 1.2 ± 0.1 $<1.38 \pm 0.35$ 0.9 ± 0.3	Schwerer et al. [14] Vuletin et al. [11] Rigaud et al. [10] Kantele, Valkonen [7]
$^{138}\text{Ba}(n, \gamma)^{139}\text{Ba}$	1.21 ± 0.21	1.62 ± 0.28	1.10 ± 0.11 0.7 ± 0.1 1.0 ± 0.2 1.12 ± 0.22 1.30 ± 0.39	Schwerer et al. [14] Vuletin et al. [11] Cuzzocrea et al. [36] Majumder [37] Perkin et al. [33]
$^{186}\text{W}(n, \gamma)^{187}\text{W}$	0.83 ± 0.20	0.80 ± 0.16	2.2 ± 0.5 1.1 ± 0.4	Schwerer et al. [14] Valkonen [29]
$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	1.09 ± 0.23		2.1 ± 1.2	Schwerer et al. [14]

intensity of this line in the ^{139}Ba decay seems at present to be uncertain. We have applied the decay parameters adopted in the NDS compilation [42]. However, in a recent survey [47] the value $I_\gamma = 18.8 \pm 2.4$ per 100 decays is tabulated. This value would bring the present activation cross-section up to 1.42 ± 0.23 mb.

The present results agree quite well with the cross-sections derived from the spectrum measurements. The comparison is of particular interest for ^{127}I , ^{186}W and ^{197}Au because a difference between σ_{act} and σ_{int} , as previously observed, might be taken as evidence for γ -ray cascades through unbound states. It is obvious from Table II that neither for ^{127}I nor for ^{186}W can a difference be settled. Furthermore, our value for ^{197}Au agrees with $\sigma_{\text{int}} = 0.9$ mb obtained in earlier spectrum measurements [5].

The general trend of the 14–15 MeV capture data for medium-weight and heavy nuclei is a rather constant cross section of about, or somewhat below, 1 mb. The exceptions might be nuclei with $N \sim 82$, e.g. Ba, La and Ce, for which the spectrum results indicate values in the range 1.3–1.6 mb. It seems that the activation results show the same enhancement for these nuclei. This behaviour might be attributed to the semidirect capture mechanism and the excitation of the giant dipole resonance (GDR). The resonance energy is about 15 MeV for the nuclei with $N \sim 82$. This implies that the semidirect cross-section is near its maximum at $E_n \approx 14$ –15 MeV. For neighbouring, deformed nuclei the GDR becomes split into two components and the strength distributed over a wider excitation energy region. The wider strength distribution results in a decrease of a maximum cross-section.

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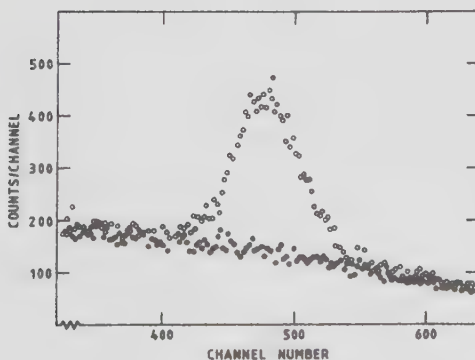
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ABSOLUTE MEASUREMENTS OF SOME NEUTRON ACTIVATION
CROSS SECTIONS IN ^{27}Al , ^{115}In AND ^{197}Au AT 14.9 MeV

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ABSTRACT

Cross sections of the reactions $^{27}\text{Al}(n,p)^{27}\text{Mg}$, $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ and $^{197}\text{Au}(n,2n)^{196}\text{Au}$ have been measured for 14.9 MeV neutrons with the activation technique. The n-p scattering cross section has been used to determine the neutron flux and the recoil protons were detected in a counter telescope system. A computer code, EFFINT, has been written to facilitate the calculation of the absolute telescope efficiency.

1. INTRODUCTION

In fast neutron cross section measurements with activation technique it is necessary to determine the absolute yield of neutrons produced in mono-energetic sources. This is often done by using a reference reaction. The choice of reference reaction depends on the reaction to be studied with respect to gamma decay and half-life.

The most frequently used reference reaction is $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, but in some cases, for example capture cross section measurements in indium and gold, it can be of advantage to use the reactions $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ and $^{197}\text{Au}(n,2n)^{196}\text{Au}$.

This paper reports activation cross section measurements of $^{27}\text{Al}(n,p)^{27}\text{Mg}$, $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ and $^{197}\text{Au}(n,2n)^{196}\text{Au}$ at 14.9 MeV. A proton recoil telescope was used to determine the neutron flux. Consequently the measured activation cross sections are referred to the well-known n-p scattering cross section in a hydrogenous material. The studied reactions are used as reference reactions in neutron capture cross section measurements at this laboratory^{1,2,3}.

2. EXPERIMENTAL ARRANGEMENTS

The neutron irradiation of the samples was performed in a vacuum chamber. The arrangement is fully described in Ref. 2.

The neutrons were produced in the $\text{T}(d,n)^4\text{He}$ reaction. The deuterons were accelerated to about 360 keV by a 500-kV Van de Graaff accelerator. Beam currents up to 5 μA were used. The beam spot diameter was typically 2 mm. Tritiated titanium targets (1.4 mg/cm^2) on a 0.02-mm-thick aluminium backing were used. The average neutron energy was $14.9 \pm 0.2 \text{ MeV}$. The energy spread was calculated from the

irradiation geometry taking into account the dependence of the neutron energy on the emission angle and the deuteron energy loss in the titanium layer ^{4,5}). The calculated energy distribution of neutrons over the sample is shown in Fig. 1.

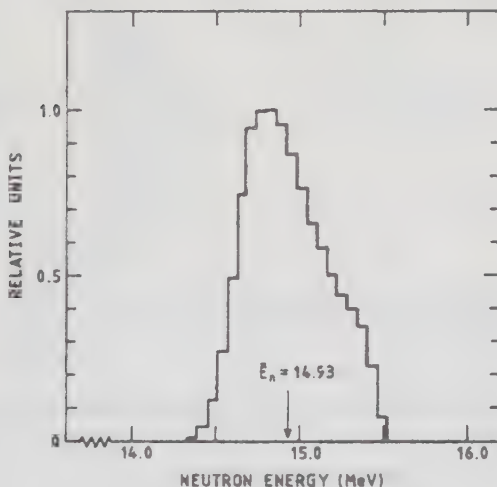


Fig. 1 The relative energy distribution of neutrons over the sample.

The irradiations were performed with a target-to-sample distance of 10 mm and a sample diameter of 10 mm. The sample thicknesses were typically 0.2 - 0.5 mm. The sample was placed in the forward direction with respect to the incident deuterons. The time variation of the neutron flux during irradiation was measured by using a long counter and was observed to be constant within 5%. The integrated neutron flux was measured by placing the telescope in an angle of 53° . Since the neutron flux is slightly anisotropic, a correction has to be made due to the difference in measuring angle between the sample and the telescope. The correction amounts to 2.6% ⁵⁾. The experimental arrangement is illustrated in Fig. 2.

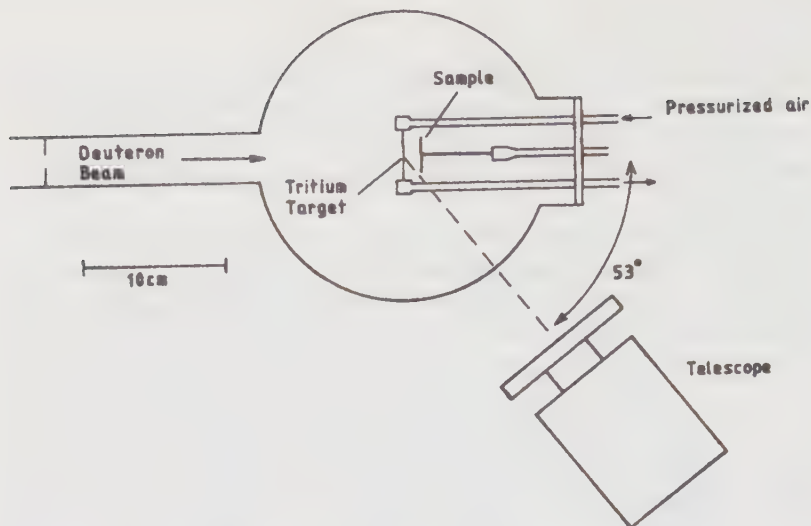


Fig. 2 The experimental arrangement. The chamber is fully described in Ref. 2.

The telescope is of the well-known Los Alamos type which is described in Ref. 6 and 7. A schematic figure of the telescope is shown in Fig. 3

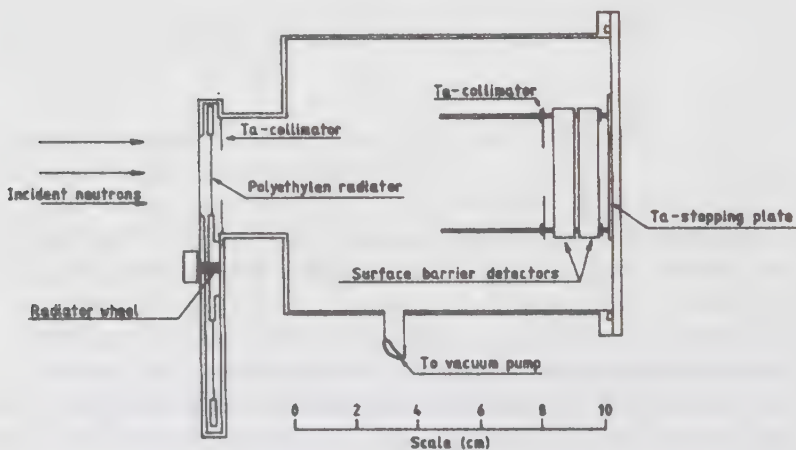


Fig. 3 A schematic lay out of the telescope.

and the electrical arrangement in Fig. 4.

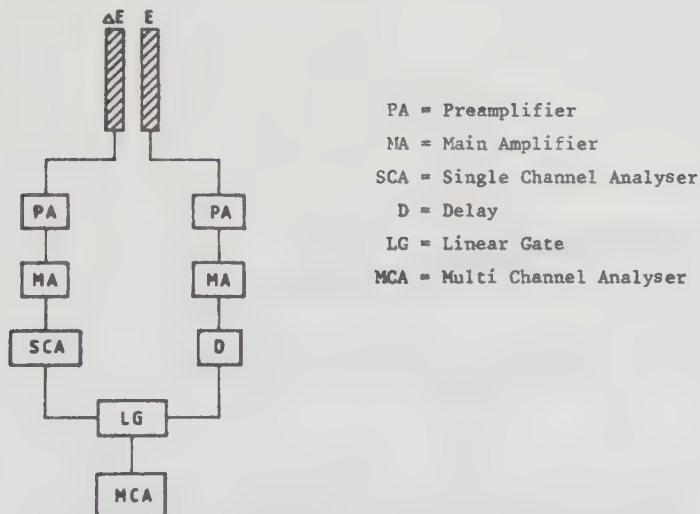


Fig. 4 Block diagram of the electronic arrangement.

Protons were scattered out of the hydrogenous (polyethylen) material by the n-p scattering process. Two surface barrier detectors (ΔE and E in Fig. 4) are used for detection of the protons. A part of the proton energy is deposited in the ΔE -detector. The signal is amplified and analysed in a single-channel analyser. The standard pulse opens the gate. Pulses from the E-detector are amplified and delayed. When the gate is opened, pulses from the E-detector can pass through to the multi-channel analyser. By using this coincidence arrangement background pulses from (n,p) and (n, α) reactions in the detectors can be reduced. The thicknesses of the used detectors were 700 μm (E-detector) and 86.1 μm (ΔE -detector).

A measurement of the background of the telescope was performed after each sample irradiation by an equivalent run, regarding beam current and irradiation time, but without any hydrogenous material in the telescope. A spectrum of recoil protons together with background is pictured in Fig. 5.

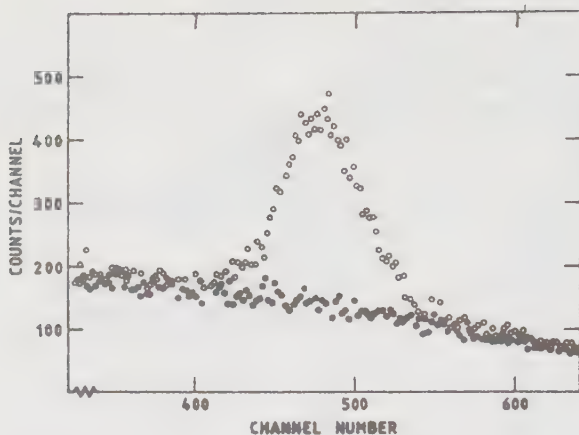


Fig. 5 A pulse-height spectrum of recoil protons. Open circles denote the spectrum obtained with polyethylen foil in the telescope and filled circles show the particle background spectrum.

The telescope efficiency for neutrons was calculated with a computer code, EFFINT, which is described in Appendix. In order to check the computer code the neutron flux was determined for different telescope-to-target distances. The result indicates within the limits of accuracy a constant neutron flux ($\text{s}^{-1} \cdot \text{sr}^{-1} \cdot \mu\text{A}^{-1}$) versus distance.

The neutron flux was obtained by subtracting the background from the spectra measured during the irradiation of the samples (Fig. 5) and by using the absolute efficiency of the telescope. The flux was found to be about $1 \cdot 10^7 \text{ s}^{-1} \cdot \text{sr}^{-1} \cdot \mu\text{A}^{-1}$.

The gamma-rays from the induced activity were measured by a $36 \text{ cm}^3 \text{ Ge(Li)}$ spectrometer. The absolute detector efficiency was determined by utilizing calibrated radioactive sources at the same position as used for the samples.

The neutron irradiation was performed with the samples (indium, aluminium and gold) attached together. Because of gamma-rays close in energy in In and Au (Table I), the

TABLE I: Decay properties required for cross section determination.

Sample				Decay-data		
Reaction	Material	Purity (%)	Abundance (%) (Ref. 19)	Energy (keV)	Half-life	Intensity ^{a)} (%) Ref.
$^{27}\text{Al}(n,p)^{27}\text{Mg}$	Al	99.7	100	843.8	9.462 M	71.8 ± 0.4 16
				1014.4		28.2 ± 0.4
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	Al	99.7	100	1368.53	15.020 H	100 16
$^{115}\text{In}(n,n')^{115m}\text{In}$	In	99.95	95.72	336.2	4.486 H	45.9 ± 0.1 17
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	Au	99.9	100	333.0	6.183 D	24.1^b 18
				355.7		87.7
				426.0		6.7

a) Photons per 100 decays of reaction product nuclei.

b) Information about uncertainties in the intensities has not been found.

Au-sample was separated from the In/Al samples before performing the gamma-ray analyses.

The peak areas in the gamma-ray spectra were calculated and the correction factors for self-absorption in the samples were calculated by using a computer-code GAMMAT⁸⁾.

Decay properties required for cross section determination are summarized in Table I.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The cross sections calculated from the experimental results are given in Table II and III together with previous results reported in the literature. The present cross section results are weighted mean values of several measurements.

TABLE II: Comparison of experimental neutron cross sections (mb) at 14.9 MeV.

Reaction	Present $E_n = 14.9$ MeV	Bormann et al. Ref. 9 $E_n = 14.9$ MeV
$^{27}\text{Al}(n,p)^{27}\text{Mg}$	68 ± 4	75 ± 7
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	113 ± 6	111 ± 4
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	2295 ± 116	2250 ± 120

Table II summarizes the results for the (n,p) and (n, α) reactions in ^{27}Al and the (n,2n) reaction in ^{197}Au . Our results show good agreement with the values recommended by Bormann et al.⁹⁾. These values were evaluated from available experimental data in the literature. The amount of experimental cross section data used in the evaluation is extensive for the (n,p) and (n, α) reactions in ^{27}Al and the different measurements show agreement within the limits of

accuracy. In the case of the $^{197}\text{Au}(n,2n)^{196}\text{Au}$ reaction the published results are scarce but show agreement. The cross section values given in the evaluation have been obtained by calculating the weighted mean values.

TABLE III: Comparison of experimental cross sections (mb) for the reaction $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ at 14-15 MeV.

	E_n (MeV)	$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ (mb)
Menlove et al. (Ref. 10)	14.96	61.6 ± 6.3
Barral et al. (Ref. 11)	14.8	69 ± 5
Santry et al. (Ref. 12)	14.7	54.5 ± 2.2
Present	14.9	65 ± 4

The present results of the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ cross section are given in Table III together with the results of recent measurements. We find good agreement within the limits of accuracy for the different measurements ^{10,11, present} except for the result of Santry and Butler ¹²⁾, who obtained a rather low cross section for this reaction. A comparison of the experimental arrangements and the decay data given in the different papers ^{10,11,12)} gave no explanation to this discrepancy.

Secondary low-energy neutrons produced in $(n,2n)$ and (n,n') reactions in surrounding material and in the sample itself may influence the (n,n') cross section in ^{115}In , since the threshold of the reaction is rather low (0.33 MeV). In the present measurements no influence of secondary neutrons from the surrounding material has been found. The influence of secondary neutrons produced in the sample itself has been studied by observing the dependence of the sample thickness on the apparent cross section. The results indicate a rather weak contribution. A sample thickness of 1 mm In gives a correction of 1.6 mb.

The cross sections measured in this work have uncertainties up to 6%. The sources of uncertainty are indicated in Table IV and V. The major sources were the uncertainties in the determination of the neutron flux, the uncertainty in the absolute photo-peak efficiency of the Ge(Li) detector and in some cases the uncertainty in determining the peak-areas. The uncertainties in weighing the samples, timing, self-absorption and in the geometrical arrangement have also been taken into account. The uncertainties in decay scheme for the case of $^{197}\text{Au}(n,2n)^{196}\text{Au}$ are not included, since no such information was found. The uncertainties should, however, be small because γ -rays with fairly well-known decay characteristics were used.

TABLE IV: Contributions to the uncertainty of the telescope efficiency.

Source of uncertainty	Uncertainty contribution %
n-p cross-section	1.0
Distance radiator-to detector	1.0
Distance neutron- source-to-radiator	1.5
Number of hydrogen nuclei	1.0
Numerical integration	0.5

TABLE V: Contributions to the uncertainty of the activation cross section.

Source of uncertainty	Uncertainty contribution %
Decay factors	0.5
Efficiency of Ge(Li)	2.0
Counting statistics (gamma-rays)	1.5 - 6
Counting statistics (recoil protons)	1.3
Telescope efficiency	4.4
γ -emission per decay	see Table I

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APPENDIX

EFFINT - A computer-code used for calculation of the absolute recoil proton telescope efficiency.

The internal geometrical arrangement of the telescope is shown in Fig. 6 together with notations used in the code.

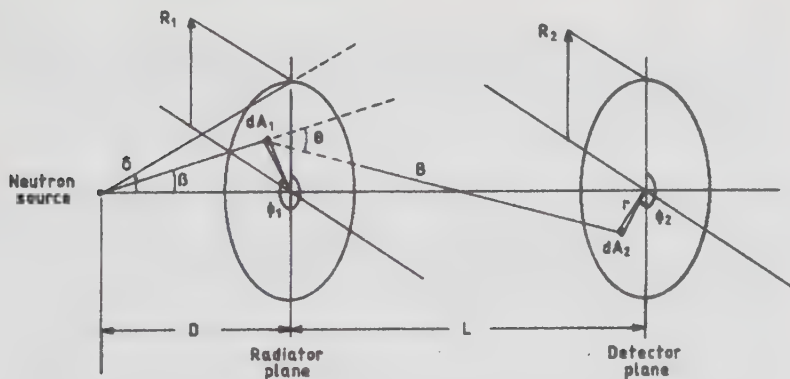


Fig. 6 The internal geometry of the telescope together with notations used in the code EFFINT.

The efficiency can be expressed by the simple formula

$$\epsilon_T = P \cdot \sigma_T(E) \cdot M \quad (\text{Ref. 6})$$

- P is the number of hydrogen nuclei in the radiator

- $\sigma_T(E)$ is the total n-p scattering cross section at energy E in the laboratory system

- M is the efficiency integral

The efficiency integral M, given in Ref. 6, has been solved by a Monte-Carlo method. The integration is mathematically accurate to 0.5% or better, for the amount of random numbers used in this work.

The total n-p scattering cross section values are calculated from the semi-empirical formula of Gammel ¹³⁾. The values obtained with this formula correspond very well with the experimental cross sections evaluated by Horsley ¹⁴⁾.

The laboratory differential scattering cross section in barns per steradian, at laboratory angle θ , is given by

$$\sigma(\theta, E) = \frac{\sigma_T(E) \cdot \cos \theta}{\pi} \cdot \frac{1 + 2 \cdot (E/90)^2 \cdot \cos^2 2\theta}{1 + (2/3) \cdot (E/90)^2}$$

The calculated efficiencies have been compared to those obtained by Bame et al. ¹⁵⁾ and the comparison is given in Table VI. The agreement is in all cases better than 1%.

Figure 7 shows the variation of the efficiency with the distance telescope (radiator)-to-target for different internal distances, L (fig. 6), in the telescope at a neutron energy of 14.0 MeV.

The input data to the program are the geometrical parameters D, L, R_1 and R_2 (as indicated in Fig. 7), the number of hydrogen nuclei in the radiator, the neutron energy and the desired amount of random numbers in the integration with the Monte-Carlo method.

TABLE VI: A comparison between the values of M calculated with the computer code EFFINT and values given in Ref. 15. The notations are from Fig. 5. The M -values are calculated for the case of $R_1/R_2 = 1$.

E_n (MeV)	D (cm)	L (cm)	δ (deg.)	L/R_1	$M_{\text{TABLE 15}}$ $\times 10^{-6}$	M_{EFFINT} $\times 10^{-6}$	$\frac{M_{\text{TABLE}} - M_{\text{EFFINT}}}{M_{\text{TABLE}}}$ (%)
4.0	22.91	11.20	2	14	19.36	19.47	-0.57
4.0	11.44	11.20	4	14	77.30	77.12	0.23
4.0	4.54	11.20	10	14	480.0	480.0	0
4.0	22.91	6.40	2	8	58.02	57.87	0.26
4.0	11.44	6.40	4	8	231.5	233.0	-0.65
4.0	4.54	6.40	10	8	1434.0	1430.0	0.28
9.0	22.91	11.20	2	14	19.55	19.46	0.46
9.0	11.44	11.20	4	14	78.06	77.98	0.10
9.0	4.54	11.20	10	14	484.0	484.0	0
9.0	22.91	6.40	2	8	58.56	58.63	-0.12
9.0	11.44	6.40	4	8	233.6	232.7	0.39
9.0	4.54	6.40	10	8	1445.0	1445.0	0
14.0	22.91	11.20	2	14	19.89	19.96	-0.35
14.0	11.44	11.20	4	14	79.38	79.46	-0.10
14.0	4.54	11.20	10	14	492.0	493.0	-0.20
14.0	22.91	6.40	2	8	59.51	59.69	-0.30
14.0	11.44	6.40	4	8	237.2	238.5	-0.55
14.0	4.54	6.40	10	8	1464.0	1452.0	0.82
20.0	22.91	11.20	2	14	20.48	20.55	-0.34
20.0	11.44	11.20	4	14	81.67	81.88	-0.26
20.0	4.54	11.20	10	14	504.0	500.0	0.79
20.0	22.91	6.40	2	8	61.15	61.03	0.20
20.0	11.44	6.40	4	8	243.5	241.8	0.70
20.0	4.54	6.40	10	8	1497.0	1493.0	0.27

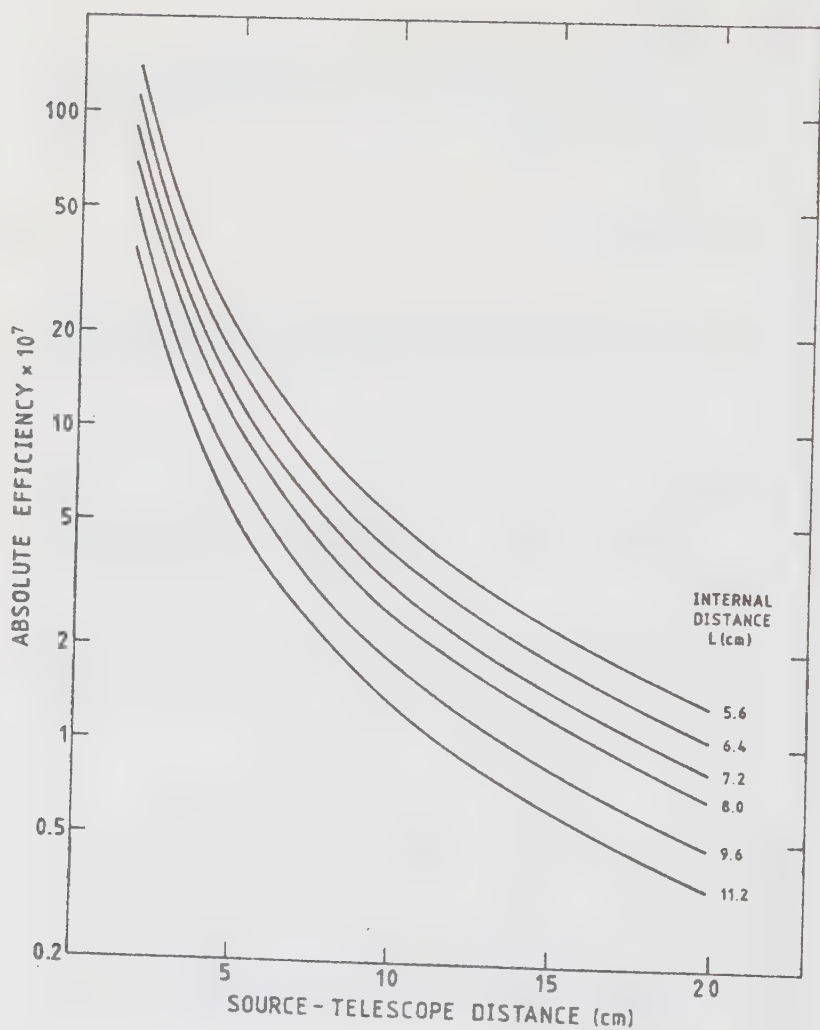


Fig. 7 The variation of the telescope efficiency with the distance between the telescope and target, D , for different internal distances, L , in the telescope at neutron energy 14.0 MeV.

[illegible]

```

10 FORMAT(5F6.2)
11 FORMAT(E12.5)
12 FORMAT(I7)
26 FORMAT(1H1,' D=',F6.2,'(CM)', ' L=',F6.2,'(CM)', ' R1=',F6.2,'(CM)
*, ' R2=',F6.2,'(CM)('// ' THE TOTAL N P SCATTERING CROSS SECTION
*AT NEUTRON ENERGY ',F6.2,' MEV IS: ',E12.6,' CM+2')
27 FORMAT(1H0,' THE NUMBER OF HYDROGEN NUCLEI IN THE RADIATOR IS:',E1
*2.6,' CM-2'// ' THE AMOUNT OF RANDOM NUMBERS IS: ',I7)
28 FORMAT(1H0,' THE EFFICIENCY IS: ',E12.6,' SR')
29 FORMAT(1H0,' THE M-VALUE IS: ',E12.6)
REAL L
DATA LIN,LUT/5,6/

```

```
C      INPUT DATA

      READ(LIN,10) D,L,R1,R2,E
      READ(LIN,11) P
      READ(LIN,12) N

C      CALCULATE THE TOTAL NP CROSS SECTION ACCORDING TO GAMMEL

      PI=3.14159263
      AA=(.0001307*E*E+.09415*E-1.860)**2+1.206*E
      BB=(.4223+.130*E)**2+1.206*E
      ZIGMA=(3*PI/AA+PI/BB)*1.0E-24
      DELTA=ATAN(R1/D)
      SUM=0.0
      CONST=R2*DELTA**4.*PI**2
      A1=PI*(1.+(2./3.)*(E/90.))**2)

C      CALCULATE THE INTEGRAL M

      DO 30 J=1,N
      BETA=DELTA*RANF(0)
      PHI1=2*PI*RANF(0)
      PHI2=2*PI*RANF(0)
      R=R2*RANF(0)
      TAN=SIN(BETA)/COS(BETA)
      B=SQRT(R**2+(D*TAN)**2+L**2-2*D*R*TAN*COS(PHI1-PHI2))
      CTETA=COS(BETA)*(L-D*TAN**2+R*TAN*COS(PHI1-PHI2))/B
      CTETB=2.*CTETA**2-1.
      A2=(1.+2.*(E*CTETB/90.))**2)/(B**3)
30 SUM=SUM+A2*R*TAN*CTETA

C      CALCULATE THE EFFICIENCY AND THE M-VALUE

      AM=CONST*L*SUM/(A1*FLOAT(N))
      EFF=AM*ZIGMA*P

C      PRINT THE RESULT AND THE INPUT DATA

      WRITE(LUT,26) D,L,R1,R2,E,ZIGMA
      WRITE(LUT,27) P,N
      WRITE(LUT,28) EFF
      WRITE(LUT,29) AM
      STOP
      END
```

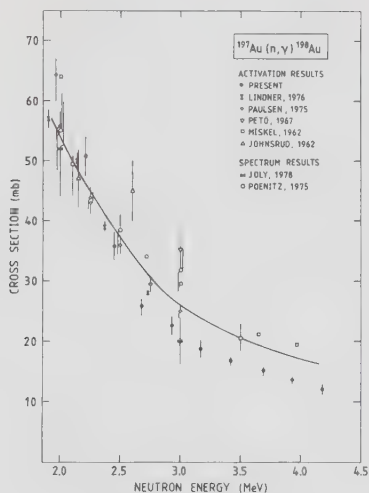
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ON NEUTRON CAPTURE CROSS SECTION MEASUREMENTS WITH THE ACTIVATION TECHNIQUE IN THE MeV REGION

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ABSTRACT

Sources of systematic errors in cross-section measurements with the activation technique have been investigated with the aid of the reaction $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$.

The main problems are related to low-energy background neutrons produced by charged-particle reactions (e.g. (p,n) and (d,n) reactions) in the target material and by nonelastic neutron reactions (e.g. (n,n') and (n,np) reactions) in the sample and surrounding materials. Methods to correct for the background neutrons have been developed and capture cross sections for ^{115}In and ^{197}Au have been determined in the energy region 2.0-4.5 MeV.

1. INTRODUCTION

Capture cross section measurements using the activation technique in the MeV region appear to be difficult primarily due to accompanying background neutron sources. On the average, the background neutrons are of a much lower energy than the primary neutrons. Since the (n,γ) cross section increases rapidly with decreasing neutron energy it means that even a small contamination by background neutrons can seriously disturb the measurements.

Studies (1-3) with 14-15 MeV neutrons indicate that the main sources of background neutrons are $(n,2n)$ and (n,n') reactions in the target backing and the sample itself in addition to the uniformly distributed flux of room-scattered neutrons. The corrections due to the secondary neutrons may be determined by systematically varying the experimental parameters. These studies show that the results of early activation measurements at 14-15 MeV are in error; in some cases by more than a factor of ten.

Numerical estimates suggest that secondary neutrons may significantly disturb the (n,γ) activation measurements also in the MeV region. It is then important to study these effects. Rather few (n,γ) cross sections have been reported for energies above 3 MeV and those below 3 MeV often show large discrepancies. The differences in the results, even for well-studied nuclei like ^{197}Au and ^{238}U , are several times greater than the quoted uncertainties which indicates the presence of serious systematic errors.

This report describes activation measurements for $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ in the energy range 2.0-4.5 MeV with the primary objective being to investigate the contributions of background neutrons and to find methods which can be used to correct for these contributions. A second objective is to apply the methods to determine the capture cross sections for ^{115}In and ^{197}Au .

The reaction $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ offers favorable experimental conditions. The $^{116\text{m}}\text{In}$ decay has a suitable half life ($T_{1/2}=54.2$ min.) and yields a γ -ray, $E_\gamma=1293$ keV, which is easy to detect. Furthermore, the capture cross section for low-energy neutrons is rather large so the activation yield is sensitive to low-energy background neutrons. It is

also an advantage that inelastic neutron scattering of ^{115}In excites a metastable state at $E_x=336$ keV with $T_{1/2}=4.5$ h. The cross section for this reaction is known to increase with energy above the threshold up to about 2.4 MeV and then to become almost constant with energy (4). Because it is a threshold reaction it is not sensitive to low-energy background neutrons, and hence the reaction can be used as a reference reaction in the activation studies.

2. EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The experimental arrangement is illustrated in Fig.1. Monoenergetic neutrons were produced either by the reaction $T(p,n)^3\text{He}$ or by $D(d,n)^3\text{He}$ with the protons or the deuterons being accelerated by a 3 MV pelletron tandem accelerator. The beam was focused onto the target with a beam spot of a diameter less than 3 mm. The current was typically $0.5 \mu\text{A}$. The beam conditions were checked during irradiation with the aid of the two apertures along the beam line. We required that the current on these apertures be less than 1% of that on the target.

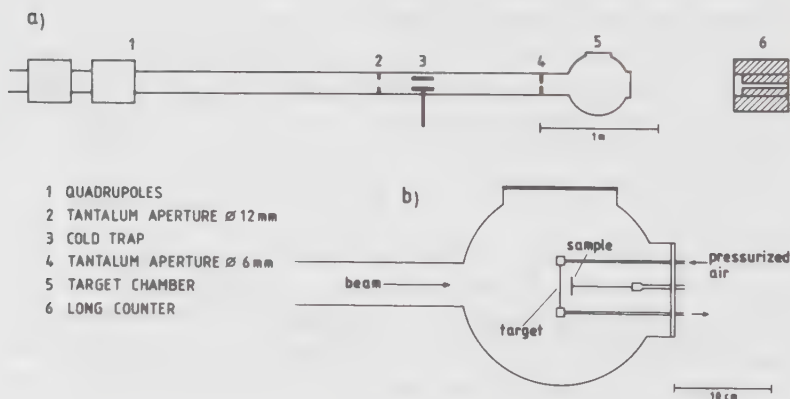


FIG.1 Experimental arrangement. The scale in a) refers only to distances between constituents of the beam line.

Solid targets were used for the measurements. The targets consisted of a thin titanium layer (about 2 mg/cm^2 in thickness), in which the hydrogen was absorbed, evaporated onto a 0.5 mm thick backing. The backing material was aluminium for the T(Ti) and tantalum for D(Ti) targets. In order to determine the background from neutrons produced by (p,n) or (d,n) reactions in the backing and absorption materials and in the apertures along the beam line, measurements were also made with targets with natural hydrogen. These targets, which we call "empty targets", were prepared in the same way and at the same time as the T(Ti) and D(Ti) targets. The irradiation of the samples took place in a target chamber which was originally made for the experiments with 14-15 MeV neutrons (3). The chamber was designed to reduce the amount of material around the target-sample region and thereby to reduce the production of secondary neutrons. A great number of samples, all circular disks, were used in the measurements.

The samples were placed at distances such that the solid angle subtended by the samples at the target was the same in all cases. For the studies of the thickness dependence of the activation yield, indium samples were used with a diameter of 10 mm and thicknesses ranging from 0.18 to 1.66 g/cm^2 . The target-sample distance dependence was determined using 0.6 g/cm^2 indium samples with diameters ranging from 5 to 20 mm. The corresponding measurements for gold were performed with samples consisting of a gold disk onto which an indium disk (about 0.2 g/cm^2 thick) of the same diameter was attached. One set of gold samples ranged from 0.2 to 2.0 g/cm^2 in thickness, all with 10 mm diameter, and another set had diameters from 5 to 20 mm with thicknesses of about 0.8 g/cm^2 .

The neutron flux was monitored by a long counter placed in the forward direction about 1.2 m from the target (5). The long counter served both as a detector of neutrons from various source reactions and as a monitor to ensure that the time variation of the neutron flux during the sample irradiations was kept below about 10%. The efficiency of the long counter was determined relative to the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ cross section for neutrons with energies between 2.0 and 4.5 MeV and was found to be constant within $\pm 5\%$ in that energy interval.

In the capture cross section measurements the samples were irradiated with neutrons from the T(Ti) target. The activation yield due to the background of primary neutrons was determined by separately irradiating a sample with the same dimensions as before with the empty target replacing the T(Ti) target. This yield was normalized to the same integrated current. The irradiation times were 0.5-1.5 h for In samples and 2-3 h for Au samples.

The γ -rays from the induced activities (Table I) were detected by an 80 cm³ open end Ge(Li) detector. As a rule, the activity is low and in order to obtain reasonably good counting statistics the sample was placed on the detector cover. This is done, however, at the expense of a good analysing geometry. With this geometry there will be relatively large corrections to the γ -ray intensities. In particular, the self-absorption of γ -rays in the sample and the cascade summing effects in the Ge(Li) detector contribute to the large correction factors. We have determined the factors experimentally for selected indium and gold samples. The samples were irradiated with neutrons of appropriate energy to obtain a relatively high yield from the induced activity. The γ -ray intensities were then measured with the sample placed at various distances, up to 10 cm, from the detector cover. We observed that already at 5 cm the corrections due to cascade summing were negligible and that γ -ray absorption in the sample could be considered to be that of the parallel beam geometry. The relative detector efficiency was determined by means of a ¹⁵²Eu source placed 5 cm from the detector. The source was also placed off-axis (at 5 cm from the detector cover) to simulate sample geometries used in this work and no variation was found in the detector efficiency. The experimental determination of the correction factors was performed to an accuracy of 2%. We also performed Monte Carlo calculations of the factors and found agreement to within 10% of the measurements.

The analysing times were typically about one hour for In and two or three hours for Au samples. The γ -ray measurements for the Au samples were delayed by about two hours after irradiation to let the intensity of the 417 keV γ -ray from the decay of ^{116m}In to become sufficiently weak so as not to disturb the measurements of the 411 keV line from the ¹⁹⁸Au decay.

The capture cross sections were determined relative to the cross section of the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ reaction, which means that neither the neutron flux nor the detector efficiency have to be measured in an absolute manner. Furthermore, it is advantageous to utilize a reference reaction which is either built-in in the sample (for indium samples) or attached to the sample (for gold samples) in such a way that the irradiation and analysis geometries will be the same for the sample and the reference.

3. RESULTS AND DISCUSSION

The main problem in (n,γ) activation experiments at 14-15 MeV concerns the influence of secondary neutrons created by reactions like $(n,2n)$ and (n,n') induced by the primary neutrons. We have found that for experiments in the MeV region primary reactions other than $\text{T}(p,n)^3\text{He}$ and $\text{D}(d,n)^3\text{He}$ cause at least as many problems as the secondary neutrons.

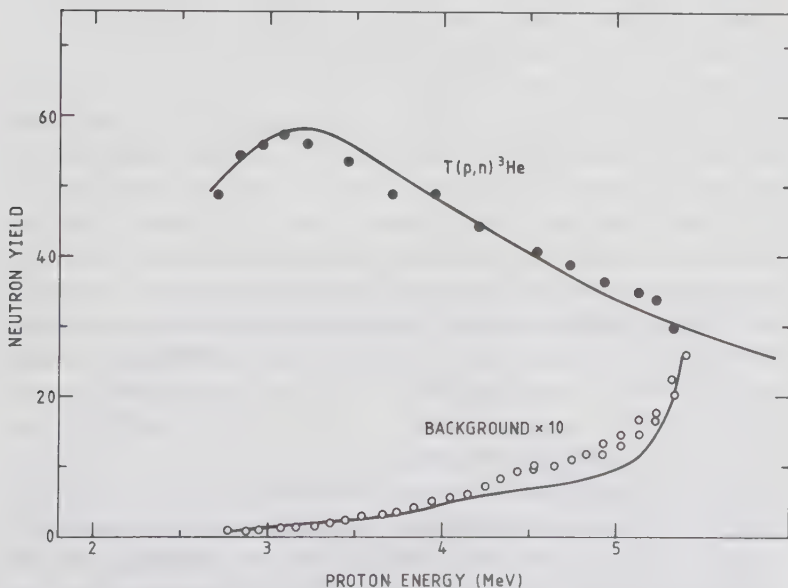


FIG.2 Neutron yields from a $\text{T}(\text{Ti})$ target and from the corresponding empty target measured by the long counter. The upper line represents the measured 0^0 cross section of the $\text{T}(p,n)^3\text{He}$ reaction (6) and the lower curve is obtained from theoretical $\text{Ti}(p,n)$ cross sections (7).

7

The main sources are (p,n) or (d,n) reactions in the target deposition and backing materials. In the first section below, this background of primary neutrons is discussed in some detail. The influence of secondary neutrons on (n, γ) activation cross sections for ^{115}In and ^{197}Au is studied in the next section followed by a note on the neutron energy spread in the measurements of the (n, γ) cross sections for ^{115}In and ^{197}Au .

3.1 BACKGROUND OF PRIMARY NEUTRONS

In the studies of the primary neutron background we started with measurements of the neutron yield by the long counter from the T(Ti) target and from the corresponding empty target. The results are shown in Fig.2. Note that the background yield is less than 1% of the T(Ti) yield for proton energies below 4 MeV (corresponding to $E_n=3.2$ MeV) but increases with energy to become greater than 10% above 5.4 MeV. As expected the yield from the T(Ti) target exhibits the same energy dependence as the σ^0 cross section (6) of the $\text{T}(p,n)^3\text{He}$ reaction (upper line). The lower line is the yield curve estimated from theoretical $\text{Ti}(p,n)$ cross sections (7). The Q-values of the various Ti-isotopes as well as of some other nuclei of interest are summarized in table II. Below $E_n=3.0$ MeV the only contribution comes from ^{49}Ti and above 3 MeV first ^{50}Ti , and then ^{47}Ti , start to contribute. The most abundant isotope, ^{48}Ti (73.9%), has its (p,n) threshold at 4.8 MeV. This gives rise to the steep increase in the yield above this energy. There should be only weak yields from other sources of primary neutron background. We have checked, by stopping the beam in a tantalum disk, that the neutron yield produced by (p,n) reactions along the beam line is negligible (less than 0.1% at $E_p=5.0$ MeV). Furthermore, there should be no background contribution from the aluminium target backing since the proton energy is below the threshold for the $^{27}\text{Al}(p,n)^{27}\text{Si}$ reaction (table II).

The background in (n, γ) activation measurements is usually much more troublesome than in the neutron yield measurements. The reason is that background neutrons on the average have much lower energies, where the (n, γ) cross section is higher, than neutrons from the source reaction ($\text{T}(p,n)^3\text{He}$ in this case). This is illustrated in Fig.3 which shows the signal-to-background (S-B) ratio observed for the reaction $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$. Note that at $E_p=4.0$ MeV the background yield is

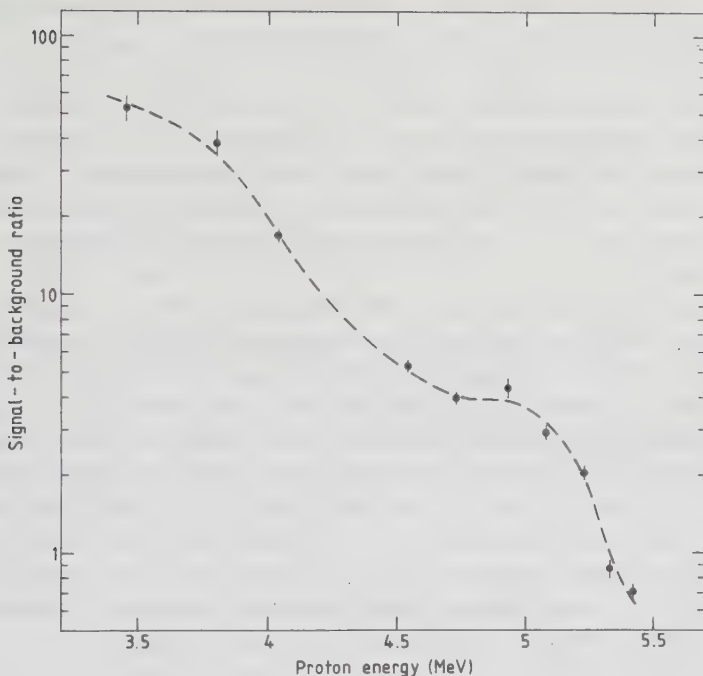


FIG.3 Signal-to-background ratios observed in activation measurements of the reaction $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$. The dashed line is drawn to guide the eye.

about 5% (corresponding to an S-B ratio of 20) in the activation measurements which is five times higher than observed for the neutron flux (Fig.2). Moreover, the S-B ratio becomes smaller than 1 for $E_p=5.4$ MeV, which is roughly an order of magnitude worse than for the neutron yield measurements.

Because of the primary neutron background, the determination of the (n,γ) activation cross section becomes increasingly uncertain with T(Tl) targets as the neutron energy exceeds 4.2 MeV (i.e. for $E_p \geq 5.0$ MeV). The background must be determined with the empty target. We have found that the Tl layer evaporated onto the aluminium backing has a very good uniformity with thickness variations of typically less than 10%. Nevertheless, the sharp increase in the primary neutron background above $E_p=5.0$ MeV implies that the measurements cannot be carried out much beyond this energy. In practice, we have set the limit

to $E_p=5.3$ MeV corresponding to $E_n=4.5$ MeV. For experiments at higher energies we have to look for other target materials.

The reaction $D(d,n)^3\text{He}$ has been used in several capture experiments both near threshold, which yields 3.0 MeV neutrons in the forward direction, and at higher energies. For the study of the background yield in connection with this source reaction we considered a solid target with deuterium absorbed in titanium and a deuterium gas target with a 4.2 mg/cm^2 thick molybdenum foil as the entrance window and gold as beam stop. The background yield was determined relative to the yield of the $D(d,n)^3\text{He}$ reaction. No measurements were actually performed with gas in a gas cell but the yield was estimated from known cross sections of the reaction. In the calculation we assumed a cell length of 1 cm and a gas pressure of $2 \cdot 10^5$ Pa. The results are compared in Fig.4 with the relative background yield from the T(Ti) target described above. The results show that above $E_n=3$ MeV deuterium targets are to be preferred to the T(Ti) targets. With solid targets the energy range can be extended by about 1 MeV and with gas targets by several MeV. Nevertheless, these targets were not used in the (n,γ) measurements presented in this report for various reasons.

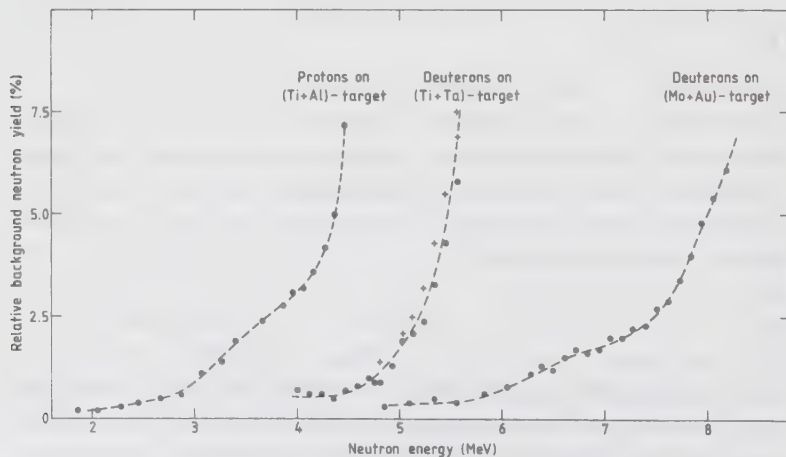


FIG.4 Relative background yields from different target arrangements as functions of the primary neutron energy.

The solid targets were evaporated onto backings of tantalum, a material which should be used with caution in these applications. Tantalum can absorb hydrogen very well and, as we found out from inconsistencies in our experimental (n,γ) results, the targets were prepared in such a way that deuterium had penetrated rather deeply into the backing. As a consequence, the energy spread of the emitted neutrons increased and the low-energy tail, due to $D(d,n)$ reactions deep in the backing material, was considerable.

Gas targets would be advantageous for (n,γ) activation measurements provided they could be made short enough and with sufficiently little material in the target-sample vicinity. The provisos are due to the importance of room-scattered neutrons, which necessitates short distances between target and sample, and of secondary neutrons produced in surrounding material. These effects will be discussed in the next section.

In the near future, we plan to use some new targets which have been prepared specifically for (n,γ) experiments in the MeV region. It is obvious from Table II that isotopically pure ^{46}Ti and ^{90}Zr , with their high (p,n) Q -values, would be much better deposition materials for tritium absorption than the natural elements. We chose ^{90}Zr , because it is commercially available in higher purity (97%) than ^{46}Ti (87%). Thus, a set of $T(^{90}\text{Zr})$ targets has been prepared. Another set of targets was made with deuterium absorbed in natural zirconium. In all cases, gold was used as the backing material. We will also try to construct a gas target cell that fulfills the requirements dictated by the need to reduce the production of secondary neutrons to a minimum.

3.2 INFLUENCE OF SECONDARY NEUTRONS

As described in considerable detail in a previous report (3) the contribution of secondary neutrons from various sources can be determined by varying the experimental parameters. One important source is (n,n') reactions within the sample itself. It can easily be shown that for thin slabs the correction due to secondary neutrons is approximately proportional to the thickness of the slab. Hence, this contribution may be studied by varying the sample thickness. This is illustrated in Figs. 5-6.

Fig.5 shows the influence on the $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ activation yield at 3.4 MeV. At this energy there is an observable contribution of secondary neutrons but it should be pointed out that the samples are somewhat thicker than normally used in activation experiments. The dashed line represents a linear fit to the data which indicates a correction of about 1 mb for a sample thickness of 1 g/cm². The slope of the line agrees quite well with the contribution of secondary neutrons which is obtained from model calculations (solid line) (11).

The calculations indicate that the thickness dependence should not be precisely linear and that the contribution at 1 g/cm² should be nearly 2 mb. According to the calculations the corrections for secondary neutrons in the sample should be approximately the same in the energy interval 2.0–4.5 MeV. We made an attempt to verify these results at 2.5

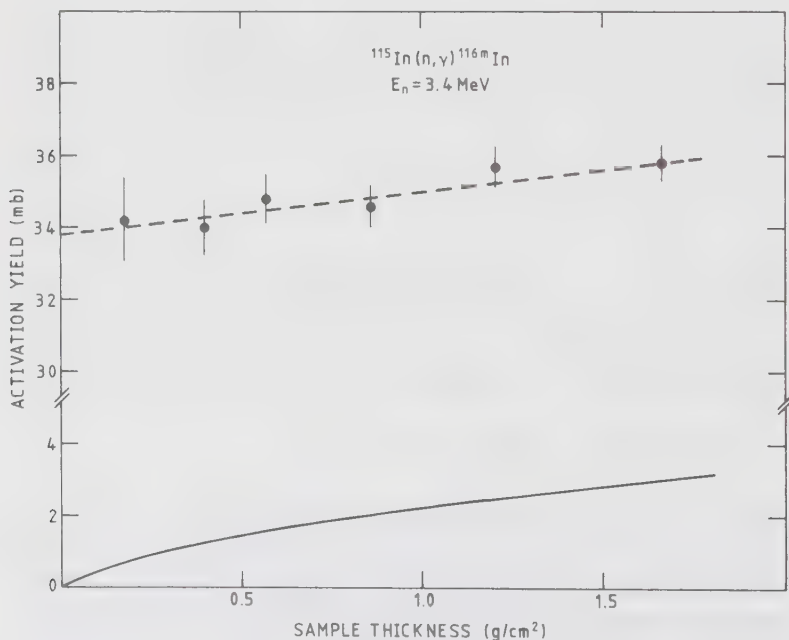


FIG.5 Dependence of the activation yield on the indium sample thickness. The dashed line is a linear least squares fit to the experimental points. The solid line shows the contribution of secondary neutrons obtained from model calculations. The error bars represent statistical uncertainties only.

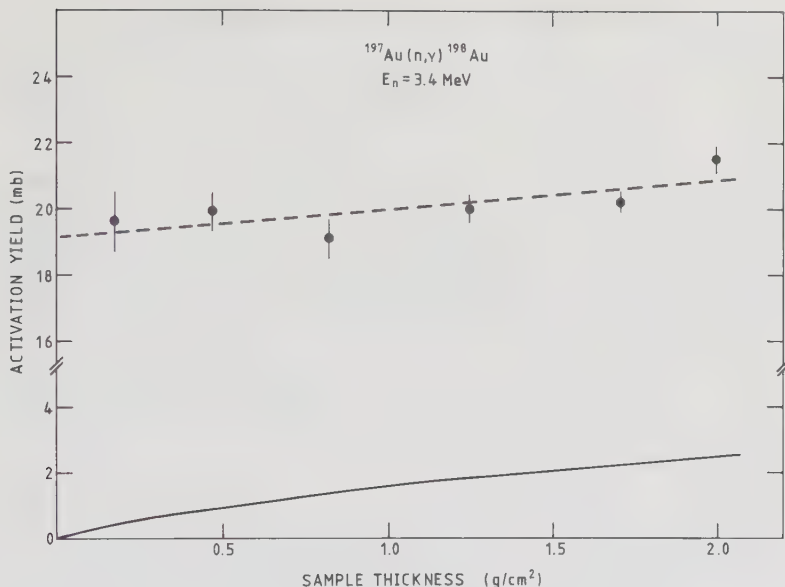


FIG.6 Dependence of the activation yield on the gold sample thickness. The dashed line is a linear least squares fit to the experimental points. The solid line shows the contribution of secondary neutrons obtained from model calculations. The error bars represent statistical uncertainties only.

and 4.5 MeV but the effects were too small to be observable with the accuracy of the present measurements.

The measurements for $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$, Fig.6, show the same thickness dependence as for ^{115}In , i.e. the linear fit indicates a contribution of about 1 mb for 1 g/cm² thick samples. The observed dependence is in reasonably good agreement with calculations.

Other important sources of secondary neutrons are (n,n') reactions in structural materials near the target-sample assembly and neutrons scattered from the walls of the room. The room-scattered neutrons should be rather uniformly distributed in the vicinity of the target. The (n,γ) activity in the sample induced by these neutrons is then constant with target-sample distance. The activity due to the primary source, assumed to be a point source, varies as $1/r^2$ whereas the contribution from neutrons scattered in the structural materials near the target and the sample should exhibit a distance dependence between

constant and $1/r^2$. Hence, the activity, $I(r)$, should be given by

$$I(r) \sim \sigma_0 \phi_0(r) + \langle \sigma_{\text{room}} \rangle \phi_{\text{room}} + \langle \sigma_{\text{sec}} \rangle \phi_{\text{sec}} \quad (1)$$

where ϕ_0 is the primary neutron flux, ϕ_{room} and ϕ_{sec} are the room-scattered and secondary fluxes and σ_0 , σ_{room} and σ_{sec} are (n, γ) activation cross sections corresponding to primary, room-scattered and secondary neutrons, respectively. The activation yield, $Y(r)$, is obtained by normalizing to unit incident flux

$$Y(r) = \sigma_0 + c_1 r^2 + c_2 f(r) \quad (2)$$

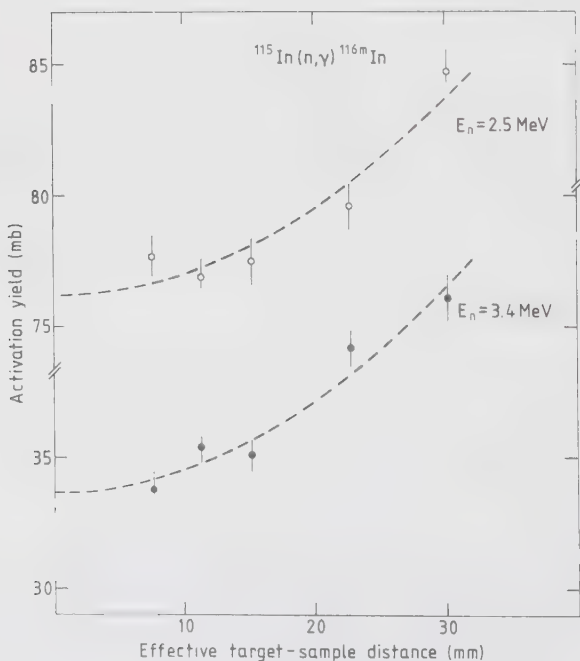


FIG.7 Dependence of the activation yield for $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ on the effective target-sample distance. This distance is calculated as the average value weighted over the beam spot on the target and over the sample. The dashed curves are r^2 least squares fits to the experimental points. The error bars represent statistical uncertainties only.

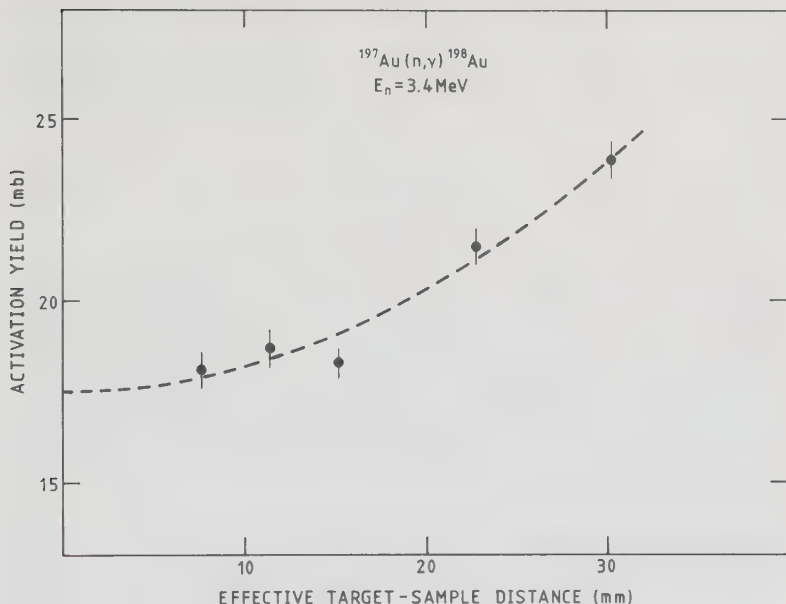


FIG.8 Dependence of the activation yield for $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ on the effective target-sample distance. This distance is calculated as the average value weighted over the beam spot on the target and over the sample. The dashed curve is an n^2 least squares fit to the experimental points. The error bars represent statistical uncertainties only.

By studying the dependence of the activation yield on the target-sample distance one may determine the contribution of room-scattered and secondary neutrons from sources outside the sample itself. Extrapolation to zero distance gives the corrected cross section.

The results of measurements of the activation yield at various sample distances between 8 and 30 mm for ^{115}In at 2.5 and 3.4 MeV and for ^{197}Au at 3.4 MeV are shown in Figs.7 and 8. For these measurements we mounted three samples at distances of 8, 15 and 30 mm in one batch for simultaneous irradiation and two samples at 11 and 23 mm in another batch. The slight increase in the contribution from secondary neutrons produced in the samples may be estimated from the thickness dependences, Figs.5 and 6.

The distance dependence is in all cases rather strong. The room-scattered background seems to dominate at the large distances and the experimental points can be reasonably well fitted by an r^2 function (dashed curves). There is no obvious contribution of a linear term as was the case in the 14-15 MeV experiments (1,3). This contribution should be weak with the target-sample arrangement used in this work. In order to study it, one has to perform measurements at distances well below 8 mm. A noticeable result is that the magnitude of the room-scattered background for ^{115}In is the same at 2.5 and 3.4 MeV, e.g. it is about 3.5 mb at a distance of 20 mm in both cases. The measurements at 4.5 MeV indicate roughly the same result although the uncertainty of the experimental points is rather large. This leads us to believe that the intensity and energy distribution of the room-scattered neutrons are approximately independent of the primary neutron energy in this energy range.

In conclusion, we have found that the contributions from secondary neutrons, from the sample itself and from surrounding materials, may be determined by varying the sample thickness and the target-sample distance. For reasonably thick samples, about 0.5 g/cm², we observe a fairly weak effect due to secondary neutrons produced in the sample. The influence of room-scattered neutrons is greater. However, it can be reduced significantly by surrounding the target chamber with a thin (about 0.25 mm thick) cadmium sheet. The results indicate that the magnitude of the contributions from secondary and room-scattered neutrons are approximately constant with primary neutron energy between 2.5 and 4.5 MeV. More data are needed to show how the contributions vary over a wider energy region.

3.3 NEUTRON ENERGY SPREAD

Because of the low (n,γ) activation yield it is necessary to position the samples as close to the target as possible while still obtaining an acceptable neutron energy resolution. In this experiment, the irradiation of all samples was made with a fixed solid angle subtended by the sample at the target. Hence, the energy distribution of the neutrons from the $T(p,n)^3\text{He}$ reaction is the same for all samples at a given proton energy. We have used a computer program, NENINA, to calculate the distributions for various incident proton energies (12). The program takes into account the proton energy degradation in the

deposition layer and the variation of neutron intensity and energy with emission angle. The result of the calculation for an incident energy of 4.3 MeV is shown in Fig.9. The average neutron energy of the distribution is obtained from

$$\langle E \rangle = \frac{\int \Phi(E) E \, dE}{\int \Phi(E) \, dE} \quad (3)$$

where the integration is carried out over the sample area. The width of the distribution at half maximum (FWHM) is about 100 keV whereas the total spread is considerably larger. The spread remains approximately constant with energy in the range of interest in this report. The variation of the capture cross section within the energy interval given by the spread is of the order of 10-15% of the magnitude of the cross section. As has been pointed out by Lindner et al. (13) the neutron energy spread does not introduce any significant uncertainty in the measured cross section. The reason is that the cross-section variation is approximately linear within the limits of the distribution, i.e.

$$\sigma(E) = k_1 E + k_2 \quad (4)$$

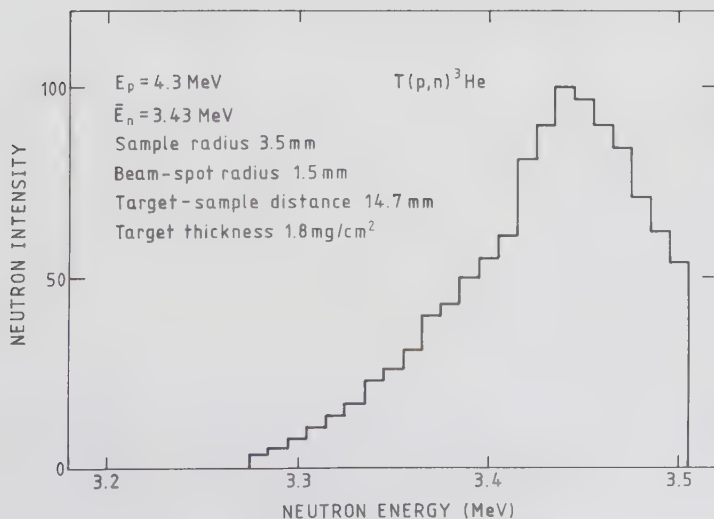


FIG.9 Energy distribution of neutrons over a sample irradiated with neutrons from the $T(p,n)^3\text{He}$ reaction.

The average cross section is given by

$$\langle \sigma \rangle = \frac{\int \Phi(E) \sigma(E) dE}{\int \Phi(E) dE} \quad (5)$$

Substitution of eq. 4 into eq. 5 leads to

$$\langle \sigma \rangle = k_1 \langle E \rangle + k_2 \quad (6)$$

This means that for any flux distribution, within the limits for which eq. 4 is valid, the average cross section equals the true cross section at $E = \langle E \rangle$.

The computer program was also used to study the variation of the energy distribution with changing radius and position of the beam spot. The variation is limited by the apertures along the beam line. Within these limits the energy spread is essentially unaffected whereas the average energy varies within ± 15 keV for a given proton energy. This corresponds to an uncertainty in the measured cross sections of $\pm 1\%$ for neutron energies above 2.4 MeV. Below 2.4 MeV the variation of the inelastic cross section may cause another $\pm 4\%$ uncertainty.

The energy of the ion beam from an electrostatic accelerator is normally very well defined. In the present case, however, we have noted sudden shifts of the terminal voltage which forced us to investigate closer any possible deviation from the nominal beam energy. We utilized the reaction $^{63}\text{Cu}(p, \gamma)^{64}\text{Zn}$ to determine the proton beam energy by means of a precise measurement of the γ -rays from the capturing state to the ground state and low-lying states with the aid of a Ge(Li) detector positioned at 90° to the proton beam. We found that the deviation could be as much as 40 keV in the extreme case. Such a deviation would be particularly harmful to the cross section measurements below 2.4 MeV because of the energy variation of the $^{115}\text{In}(n, n')^{115\text{m}}\text{In}$ cross section used as the reference. For example, a shift of 40 keV at $E_n = 2.0$ MeV corresponds to a cross section difference of about 4% which would not be acceptable in our final cross section measurements. We shall, therefore, include a particle detector in the experimental set up for surveillance of the beam energy.

3.4 CAPTURE CROSS SECTIONS

Cross sections were measured for the reactions $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ in the energy range 2.0–4.5 MeV in intervals of about 200 keV. The cross sections were determined relative to the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ cross section which was taken from ref. 4. The results are summarized in Table III and compared in Figs.10 and 11 with the results of previous experiments (13–21).

The cross sections have been corrected for contributions of secondary neutrons by using the measured dependencies of the target-sample distance and the sample thickness. The corrections were obtained by extrapolating the yield curves (Figs.5–8) to zero effective distance and zero thickness.

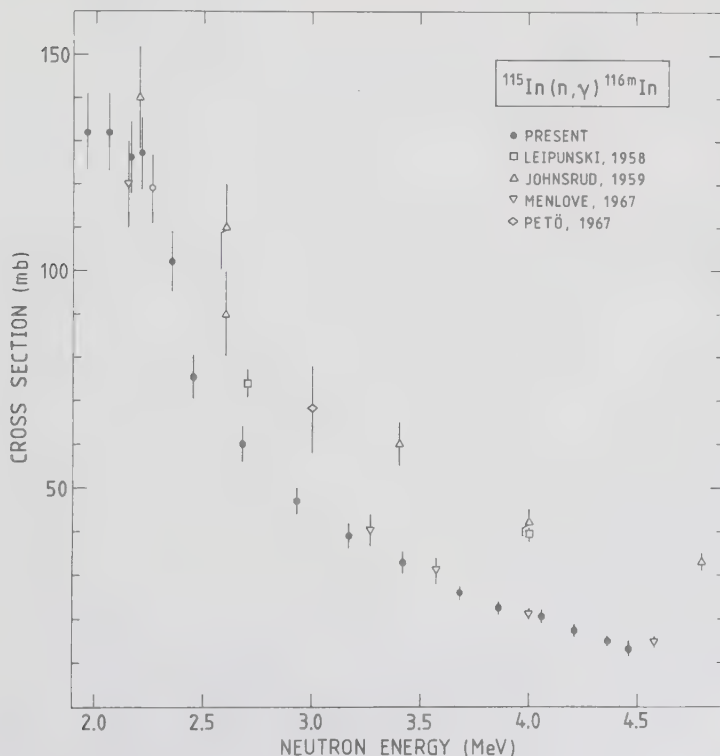


FIG.10 Cross section for the reaction $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ as a function of neutron energy.

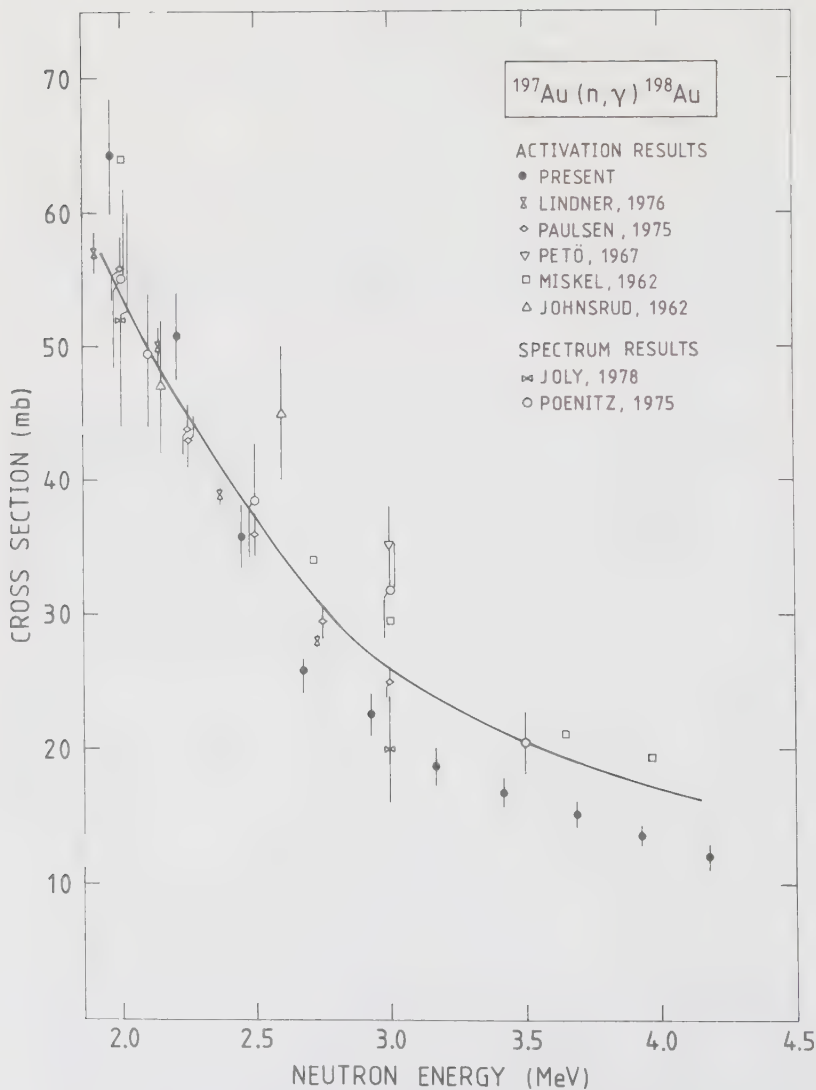


FIG.11 Cross section for the reaction $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ as a function of neutron energy. The solid curve represents the ENDF/B-V evaluation.

As discussed in Section 3.2 the magnitude of the contribution of secondary neutrons for a given sample at a given distance is approximately independent of the neutron energy in this range. The corrections amount to 2.0 mb for ^{115}In and 2.2 mb for ^{197}Au . The error bars reflect statistical uncertainties (4-5%) and uncertainties in the cross section for the reference reaction (6%). Some contribution comes from uncertainties in the relative detection efficiency (2%), in the γ -ray correction factors (2%) and in the decay and branching ratios (2%). We have not included effects due to ion beam energy shifts in the error estimates although any deviation would affect the cross section value. For the points above 2.4 MeV, the effect would be merely a displacement in energy (in extreme cases by 40 keV). Below 2.4 MeV, the magnitude of the cross section values would be influenced, in addition to the energy displacement, by the energy variation of the reference cross section. In the case of a 40 keV shift, the cross sections near 2.0 MeV would change by about 4%. Clearly, these effects would dominate the experimental uncertainties. We consider, therefore, the present cross section results only as preliminary pending further investigations.

The present results for ^{115}In agree very well with those of Menlove et al. (14) but are significantly lower than earlier results (15-17). Menlove et al. (14) corrected for room-scattered neutrons and for neutrons scattered from the target vicinity. The influence of room-scattered neutrons was determined from measurements with long target-sample distances (0.5 and 1.0 m). The effects of neutron scattering from materials in the target vicinity (gas cell assembly, sample packet and the fission chamber) were measured in a way that may not properly account for the influence of secondary neutrons at higher energies, say above 5 MeV (See ref. 3). However, the corrections may be adequate in the range displayed in Fig.10. It seems reasonable to assume that sufficient corrections were not applied in earlier work (14). Our results for $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ are significantly lower than the curve representing the recent ENDF/B-V evaluation for neutron energies above 2.5 MeV. In this range we observe reasonably good agreement with recent activation results by Lindner et al. (13) and Paulsen et al. (18). The present values at 2.0 and 2.2 MeV seem suspiciously high which may indicate problems related to the ion-beam energy discussed above.

ACKNOWLEDGEMENTS

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TABLE I. Decay data for the γ -rays utilized in the present work

REACTION	ENERGY (KeV)	HALF-LIFE (s)	INTENSITY (%)	REF.
$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$	1293.54	3247 ± 3	85 ± 2	(8),(9)
$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	336.0	16150 ± 14	45.9 ± 0.3	(10)
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	411.80	232848 ± 173	95.55 ± 0.08	(10)

TABLE II. Suitable materials for the preparation of mono-energetic neutron sources either as solid or gas-filled targets.

NUCLIDE	ABUNDANCE (%)	DEPOSITION LAYER			BACKING		
		Q-VALUE (MeV)		COULOMB BARRIER (MeV)	Q-VALUE (MeV)		COULOMB BARRIER (MeV)
		(p,n)	(d,n)		(p,n)	(d,n)	
²⁷ Al	100				-5.59	9.36	3.3
⁴⁶ Ti	7.9	-7.84	2.95				
⁴⁷ Ti	7.3	-3.70	4.61				
⁴⁸ Ti	73.9	-4.80	4.54	4.9			
⁴⁹ Ti	5.5	-1.8	5.72				
⁵⁰ Ti	5.3	-3.0	5.83				
⁹⁰ Zr	51.5	-6.89	3.04				
⁹¹ Zr	11.2	-1.93	3.63				
⁹² Zr	17.1	-2.79	3.81	7.5			
⁹⁴ Zr	17.4	-1.69	4.58				
⁹⁶ Zr	2.8	-0.57	5.24				
⁹² Mo	15.8				-8.84	1.86	
⁹⁴ Mo	9.0				-5.04	0.81	
⁹⁵ Mo	15.7				-2.44	3.41	
⁹⁶ Mo	16.5				-3.72	2.12	7.8
⁹⁷ Mo	9.5				-1.08	4.77	
⁹⁸ Mo	23.8				-2.37	3.48	
¹⁰⁰ Mo	9.6				-1.12	4.72	
¹⁸¹ Ta	100				-1.00	4.80	
¹⁸² W	26.4				-3.64	2.31	
¹⁸³ W	14.4				-1.65	2.78	
¹⁸⁴ W	30.6				-2.41	3.17	11.5
¹⁸⁶ W	28.4				-1.32	3.77	
¹⁹² Pt	0.8				-4.30	2.18	
¹⁹⁴ Pt	32.9				-3.29	2.89	
¹⁹⁵ Pt	33.8				-1.01	2.89	11.8
¹⁹⁶ Pt	25.3				-2.26	3.60	
¹⁹⁸ Pt	7.2				-1.09	4.24	
¹⁹⁷ Au	100				-1.55	4.86	11.9

TABLE III. The present cross section results together with data for the reference reaction used (4).

E_n (MeV)	RESULTS				REF. REACTION	
	$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$		$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$		$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	
	σ	$\Delta\sigma/\sigma$	σ	$\Delta\sigma/\sigma$	σ	$\Delta\sigma/\sigma$
	(mb)	(%)	(mb)	(%)	(mb)	(%)
1.96	132	6.8	64.3	6.8	262	6.1
2.06	132	6.9			287	6.1
2.16	126	6.8			313	6.0
2.21	127	6.8	50.8	6.5	319	6.0
2.26	119	6.8			323	6.0
2.35	102	6.8			330	6.0
2.45	75.4	6.7	35.8	6.8	336	6.0
2.68	60.0	6.9	25.8	6.7	343	6.0
2.93	47.0	6.9	22.6	6.9	348	6.0
3.17	39.0	8.2	18.7	8.0	348	7.3
3.42	32.9	8.1	16.8	8.0	341	7.3
3.68	26.3	7.7			336	6.0
3.69			15.2	7.0	336	6.0
3.86	22.4	7.7			328	6.0
3.93			13.6	7.2	329	6.0
4.06	20.4	8.0			327	6.0
4.18			12.0	7.8	325	6.0
4.21	17.3	8.0			325	6.0
4.36	15.5	7.9			321	6.0
4.46	13.2	15.2			321	6.0

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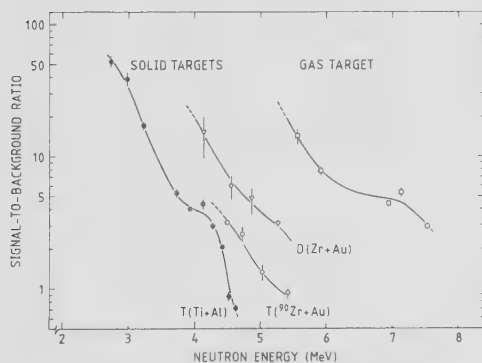
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**NEUTRON-CAPTURE CROSS-SECTION MEASUREMENTS
FOR ^{115}In AND ^{197}Au IN THE ENERGY REGION 2.0 - 7.7 MeV,
USING THE ACTIVATION TECHNIQUE.**

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ABSTRACT

The cross sections for the reactions $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ have been measured with the activation method in the energy range 2.0-7.7 MeV. The influence of background neutrons on the results has been studied in considerable detail. The main problems in the measurements are caused by low-energy neutrons generated by charged-particle reactions (e.g. (p,n) and (d,n) reactions) in the target material and by secondary neutrons (primarily (n,n') reactions) from the sample and surrounding materials. Low-mass target-sample assemblies have been constructed and methods to correct for the background neutrons have been developed.

I INTRODUCTION

We have previously reported [1] on activation measurements for the reactions $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ in the neutron-energy range 2.0-4.5 MeV. The present report describes the work performed to extend the energy range up to 7.7 MeV with the same objectives as before, namely to systematically investigate the sources of background neutrons and to find methods to correct for the contribution to the (n,γ) activation yield caused by these neutrons. We have applied the methods to determine the capture cross section for ^{115}In and ^{197}Au .

Sources of background neutrons can be divided into two categories. One type concerns secondary, low-energy neutrons that are produced by (n,n') , $(n,2n)$, etc. reactions in the sample and in the material of the surrounding structures in the target-sample assembly. This background of secondary (tertiary, quaternary, etc.) neutrons is known to be troublesome in measurements with 14-15 MeV neutrons and is expected to cause problems also in measurements at lower energies.

The other type of background is related to the neutron-source reactions. In our measurements we have utilized the reactions $\text{T}(p,n)^3\text{He}$ and $\text{D}(d,n)^3\text{He}$ for the production of monoenergetic neutrons. The projectiles may, however, also generate a background of primary neutrons from (p,n) or (d,n) reactions in the target backing, collimators etc. In the previous work [1] tritium targets were used, made by absorbing the tritium in titanium, evaporated onto an aluminium backing. It was noted that the background with these targets increased rapidly with energy starting at $E_p \approx 5.0$ MeV and it was found that it came mainly from (p,n) reactions in the most abundant titanium isotope, ^{48}Ti . The results indicate that the energy range for the (n,γ) experiment can be extended by replacing titanium by an element with a higher (p,n) threshold. A suitable deposition

material is ^{90}Zr which has as high a Q-value as 6.9 MeV. An alternative way to increase the energy range is to utilize the $\text{D(d,n)}^3\text{He}$ reaction ($Q=+3.3$ MeV). Preliminary measurements showed that deuterium targets, in particular gas targets, might be used to extend the range close to the threshold of deuteron break-up.

In this report measurements made with new solid targets and a deuterium gas-target assembly, especially constructed to reduce the primary- and secondary-neutron background, are described. The remaining contribution to the activation yield from the background neutrons was determined by systematically varying the experimental parameters. As before the reaction $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ was utilized for these investigations because it offers favourable experimental conditions. Similar measurements were performed for ^{197}Au and the results confirm the conclusions drawn for ^{115}In .

Some of the cross sections for ^{115}In and ^{197}Au in the energy range 2.0 to 2.5 MeV have also been remeasured with better accuracy. These cross sections, reported previously [1], had relatively large experimental uncertainties due to problems related to the proton-beam energy.

II EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The experimental arrangement has been described to a great extent in the previous report [1] and, therefore, only the relevant features will be mentioned here. Monoenergetic neutrons were produced either by the reaction $\text{T(p,n)}^3\text{He}$ or by $\text{D(d,n)}^3\text{He}$ with the protons and deuterons being accelerated by a 3 MV pelletron tandem accelerator. The ion-beam energy was checked before and after each irradiation by elastically scattering the beam in a $135\text{ }\mu\text{g}/\text{cm}^2$ gold target. The scattered particles were detected at 150 degrees in a surface-barrier detector subtending

a solid angle of ≈ 0.1 msr at the target.

Both solid targets and a deuterium gas-target arrangement were used in the measurements, but with different geometries in the two cases. The new solid targets, which were used for measurements in the neutron-energy ranges 2.0-2.5 MeV and 4.1-5.5 MeV, consisted of an absorption layer (about 2 mg/cm^2), in which tritium or deuterium was absorbed, evaporated onto a 0.2 mm thick gold backing. For the tritiated targets the absorption material was ^{90}Zr and for the deuterium targets natural zirconium was used. In order to determine the background from neutrons produced by (p,n) or (d,n) reactions in the backing and absorption materials and in the collimators along the beam line, measurements were also made with targets with natural hydrogen replacing ^3H or ^2H . These targets, which we call "empty targets", were prepared in the same way and at the same time as the "active" targets. The irradiation of the samples took place in a target chamber designed to minimize the amount of material around the target-sample region thereby reducing the production of background neutrons [2]. The sample parameters and the irradiation geometry were the same as in ref.[1].

The deuterium gas target, used for measurements in the energy range 4.6-7.7 MeV, is illustrated in Fig. 1. The gas cell is a tube 1 cm in length and approximately 1 cm in diameter made of 0.2 mm stainless steel with a 0.25 mm thick gold beam stop which is soldered onto the inner wall of the tube. The entrance foil is attached to the cell by means of a hollow piston. Two thin ring-shaped indium seals, one on each side of the entrance foil, are used to seal the system. A 4.2 mg/cm^2 molybdenum foil has been used in the experiments.

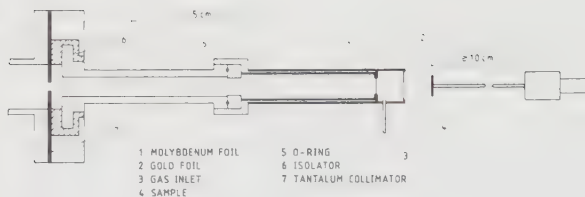


Figure 1: The deuterium-gas target arrangement.

The beam was focused onto the entrance foil with the aid of two tantalum collimators, with apertures of diameters 3 and 4 mm located 12 and 37 cm, respectively, from the foil. The current on these collimators was required to be no more than a few percent of the target current. The gas pressure was typically $4 \cdot 10^5$ Pa. Before entering the cell, the gas passed through a liquid-nitrogen cold-trap. The cell was cooled by compressed air during irradiation. Normally, the background from (d,n) reactions was determined with the cell evacuated. To check this procedure the cell was irradiated at different energies with the deuterium gas replaced by natural hydrogen.

The indium and gold samples used in the measurements with the gas target were shaped as small discs with diameters of 7.5 and 10 mm, respectively. The thicknesses varied between 0.2 and 1.9 g/cm² for the indium samples and between 0.5 and 2.0 g/cm² for the gold samples. An indium disc (0.1-0.2 g/cm²) of the same diameter was attached to the gold samples. The irradiation times were typically 0.5-1.5 hours for the indium samples and 2-3 hours for the gold samples.

Routinely, the cross sections are determined relative to the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ cross section [3]. For the neutron energies 2.1, 2.5 and 5.5 MeV the neutron flux was determined with a proton-recoil telescope. The results were applied to the

calculation of the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ reaction cross section. Agreement was obtained with the values of ref.[3] within the limits of the uncertainties (typically 10% in our measurements and 6-10% in ref.[3]). For the gas-cell measurements, very good agreement (better than 3%) was obtained between the flux determined with the telescope and that calculated from the known $\text{D(d,n)}^3\text{He}$ cross section [4], the integrated beam current, the gas pressure and the length of the cell. The neutron flux was monitored by a long counter to ensure that the time variation of the neutron flux during the sample irradiation was kept below about 10%.

The γ rays from the induced activity (see Table I) were detected with Ge(Li) detectors. Generally the activity is low and in order to obtain reasonably good counting statistics the sample was placed directly on the detector cover. With this geometry, there are relatively large corrections to the γ -ray intensities (typically 25% and 10% for the ^{115}In and ^{197}Au measurements, respectively) due to cascade summing effects and self attenuation in the sample. As described in detail in ref.[1] the corrections were determined experimentally to an accuracy of typically $\pm 2\%$. The relative detection efficiency was determined with a ^{152}Eu point source [5] while the absolute detection efficiency was measured using a set of calibrated sources (supplied by Amersham International Limited). In both cases the source was placed at 5 cm from the detector. The analysing times were typically about one hour for the indium samples and two to three hours for the gold samples.

III BACKGROUND FROM PRIMARY NEUTRONS

The yield of background neutrons from some target arrangements has previously been measured by means of a long counter whose efficiency is essentially constant over a large neutron-energy

range. The results were discussed in our previous report [1]. Typically, the background yield rises sharply at some critical energy, e.g. at $E_p \approx 5.0$ MeV for tritium targets made by absorbing tritium in titanium evaporated onto an aluminium backing (denoted 'T(Ti+Al) targets'). In this case, the rise could be attributed to the (p,n) threshold of the most abundant titanium isotope, ^{48}Ti (73.9%).

The effect on (n, γ) activation measurements is much greater than indicated by the neutron intensity alone. This is due to the fact that the energy of the background neutrons is on the average lower (where the (n, γ) cross section is higher) than the energy of the neutrons from the source reaction, $\text{T}(p,n)^3\text{He}$ or $\text{D}(d,n)^3\text{He}$. Therefore, it was decided to focus this study on the effect of the background neutrons on activation-yield measurements for the reaction $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$.

The ratio between the (n, γ) activation yield from the source reaction, Y_s , and that from the corresponding empty target, Y_b , limits the useful energy range of the target. The results of the measurements of the signal-to-background ratio, Y_s/Y_b , for some typical targets are plotted in Fig. 2 as a function of the neutron energy of the source reaction. For the T(Ti+Al) targets the ratio decreases rapidly with energy above $E_n \approx 4.2$ MeV and this drop determines the upper limit of the useful energy range for this target arrangement.

It was expected that the new tritium targets with ^{90}Zr evaporated onto a gold backing would be much better than the T(Ti+Al) targets. The reason is that the $^{90}\text{Zr}(p,n)$ threshold is high ($E_p = 6.9$ MeV), which means that below this energy (corresponding to $E_n = 5.9$ MeV for the $\text{T}(p,n)$ reaction) few background neutrons should be generated by these targets. This is, however, not the case and it seems likely that additional impurities are present.

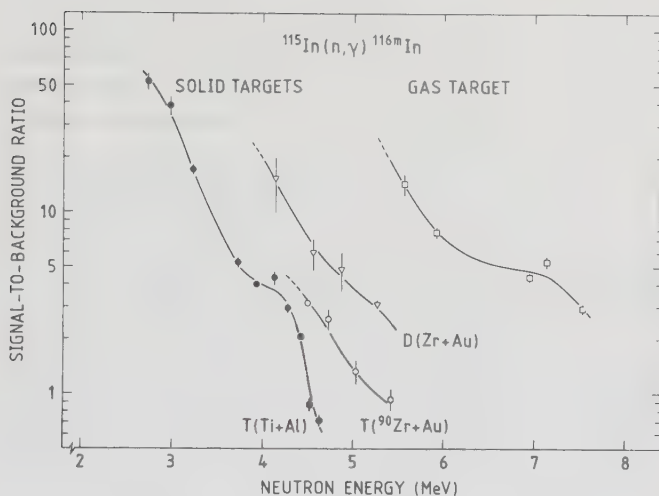


Figure 2 : Signal-to-background ratios from activation-yield measurements for the different target arrangements used. The lines are drawn to guide the eye.

The long-counter measurements indicated that the $\text{D(d,n)}^3\text{He}$ reaction ($Q=+3.3$ MeV) would be an advantageous source reaction for neutron energies above 4 MeV. It can be seen in Fig. 2 that the present results confirm this indication. The energy range can be extended several MeV, in particular with the use of the deuterium gas target. The signal-to-background ratio may be improved by increasing the gas pressure and cell length. In the present application, the pressure is as high as the molybdenum foil can withstand over reasonable run periods and the cell length is limited by the need for small target-sample distances because of the influence of secondary neutrons (see Section IV).

The useful energy range for a target system is closely related to the question of how precisely the background can be

determined by the measurements with the empty target. The solid empty targets were manufactured, as mentioned in Section II, in the same way and at the same time as the tritium and deuterium targets. They were also treated in the same way afterwards, i.e., they were exposed to the same proton or deuteron bombardment. The uniformity of the targets was found to be quite good and the reproducibility of the background yield was typically better than 10%. If this value is taken as the uncertainty in the background, the (n, γ) cross section for a signal-to-background ratio of unity will have an uncertainty of $\pm 10\%$ from this source alone. In general, this is not acceptable and one usually requires the ratio to be at least better than two or three. This requirement then limits the useful range for the $T(\text{Ti}+\text{Al})$ target to $E_n < 4.4$ MeV, for the $T(^{90}\text{Zr}+\text{Au})$ target to $E_n < 4.8$ MeV and for the $D(\text{Zr}_{\text{nat}}+\text{Au})$ target to $2.5 < E_n < 5.4$ MeV.

With solid targets there always remains an uncertainty, despite all precautions, that the empty target may not represent an adequate background target. To a large extent this uncertainty is removed with the application of a gas target since the background from (d, n) reactions in the entrance foil and the beam-stop can be determined with the gas-cell empty. With the gas cell the only difficulty encountered was a disturbing variation in the background. It was found that this was caused by local impurities on the surface of the gold beam stop (probably from the soldering of the gold disc onto the stainless steel tube). The difficulty was remedied by inserting another 0.20 mm gold disc in front of the original beam stop. In most cases the cell was emptied for the background runs ignoring the effects of energy degradation in the gas. However, by comparing the background from an empty cell with that from a cell filled with H_2 gas (of a purity of 99.9997%) for several energies, the effects could be studied. The difference in the obtained cross sections was in all cases less than 1%.

The most difficult problem with the gas target is the background related to impurities in the D_2 gas itself. The gas used was stated to have a purity of better than 99.4%, with nitrogen being the most abundant contaminant (except for hydrogen which does not affect the measurements). Measurements with the cell filled with nitrogen showed that a content of 0.6% nitrogen in the deuterium gas would give a contribution of more than 45% to the activation yield for energies above 7 MeV. Fortunately the purity of the gas was higher than stated. In an analysis performed with gaschromatography, it was found that nitrogen was the most abundant impurity with a content of 24 ppm. The contribution to the yield from such a small contamination is less than 1% above 7 MeV. The H_2 results indicate that negligible contamination of the gas occurred when passing it through the handling system.

IV BACKGROUND FROM SECONDARY NEUTRONS

A Background produced inside the sample.

As has been discussed previously, the contribution to the activation yield from secondary neutrons produced inside the sample is approximately proportional to the thickness of the sample. For reasonably thin samples the correction can therefore be determined by varying the sample thickness. To illustrate this dependence, Fig. 3 shows the activation yield for the $^{115}\text{In}(n,\gamma)^{116m}\text{In}$ reaction for different sample thicknesses ranging from 0.17 to 1.9 g/cm². Measurements have been performed for the primary-neutron energies 3.4, 4.5, 5.3 and 6.5 MeV. The results for 3.4 MeV have been reported previously [1] but are included for comparison.

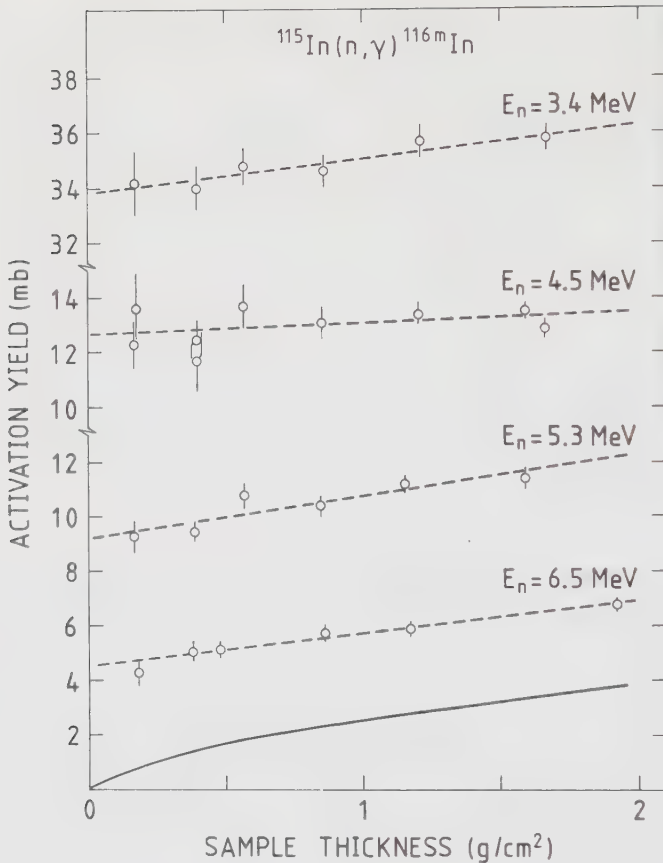


Figure 3 : Activation yield for different sample thicknesses at several primary-neutron energies. The dashed lines are linear least-squares fits to the experimental data. The solid line shows the contribution of secondary neutrons obtained from model calculations. Only statistical uncertainties are given.

It can be concluded from the figure that the contribution to the yield from secondary neutrons increases linearly with the sample thickness. The slopes of the lines are the same for the

different neutron energies, except for $E_n=4.5$ MeV. Here, the slope is about two standard deviations from the average value. However, there is no reason to believe that the deviation is anything but statistical.

The solid line in Fig. 3 represents theoretical estimates of the contribution obtained from model calculations. The model used in these calculations has been described previously [6]. It is based on a formula [7] which gives the probability, $P_C(E)$, that a neutron will make a collision on its way out of the sample. The correction, σ^{sn} , can be expressed by

$$\sigma^{sn} = \int P_C(E) I(E) \frac{\sigma_C(E)}{\sigma_t(E)} dE \quad (1)$$

where $I(E)$ is the energy distribution of secondary neutrons produced in the sample, $\sigma_C(E)$ is the capture cross section and $\sigma_t(E)$ is the total cross section. The distribution $I(E)$ is estimated from the statistical model [8]. Below the $(n,2n)$ threshold, $I(E)$ is normalized by the relation

$$\int I(E) dE = \sigma_{n,n'} + \sigma_{n,np} \quad (2)$$

The cross sections are taken from ref.[9]. The calculations agree quite well with the experimental results except for small thicknesses (less than 0.4 g/cm^2) where they give a dependence departing from linearity. This effect is, however, too small to be verified experimentally with the present arrangement.

B Background produced outside the sample.

Our earlier measurements showed a rather strong influence on the activation yield of neutrons scattered from the walls of the experimental area, in particular, as we suspected, from the wall

in the forward direction with respect to the beam. For the reason of good beam optics, the neutron target was positioned only about 1.5 m from this wall. It turned out that the correction due to these neutrons amounts to a few millibarns which may be tolerable below $E_n=4.5$ MeV where $\sigma_c > 10$ mb. At higher energies, however, these background neutrons would seriously limit the accuracy of the cross-section determination. Hence, we decided to shorten the beam line by approximately 1 m at the expense of beam quality. The result is that it requires more work to obtain a satisfactory beam spot on the target but, in return, a much weaker influence from room-scattered neutrons is obtained. This can be seen in the target-sample distance dependence of the activation yield, examples of which are shown in Fig. 4. One notes that there is a much weaker dependence both in the case of the solid target at $E_n=5.3$ MeV and in the case of the gas target at 6.5 MeV. In both cases the correction amounts to about 0.6 mb at a distance of 10 mm. The shaded area represents the contribution to the activation yield from secondary neutrons produced in the beam stop, and the unshaded area above shows the contribution from room-scattered neutrons.

The activity, $A(n,\gamma)$, induced in the sample may be described by three terms:

$$A(n,\gamma) \propto \sigma_0 \langle \Phi_0 \rangle + \sigma_{\text{sec}} \langle \Phi_{\text{sec}} \rangle + \sigma_{\text{room}} \langle \Phi_{\text{room}} \rangle \quad (3)$$

where the first term is due to capture of the primary neutrons and the other terms account for the capture of secondary neutrons. The different neutron fluxes are represented by Φ and the corresponding capture cross sections by σ . The subscript 'sec' represents neutrons scattered inelastically in the structural materials near the target and the sample, and 'room' denotes room-scattered neutrons.

The activation yield is obtained by dividing $A(n, \gamma)$ by $\langle \Phi_0 \rangle$. In practice this is done by utilizing the reaction $^{115}\text{In}(n, n')^{115m}\text{In}$ for which the influence of secondary neutrons is negligible. One then obtains

$$Y(n, \gamma) = \sigma_0 + \sigma_s \frac{\langle \Phi_{\text{sec}} \rangle}{\langle \Phi_0 \rangle} + \sigma_r \frac{\langle \Phi_{\text{room}} \rangle}{\langle \Phi_0 \rangle} \quad (4)$$

The second and third terms depend on the target-sample distance, r . To illustrate this consider a point source for which Φ_0 varies as r^{-2} . The room-scattered neutrons may be assumed to be uniformly distributed over the target-sample area, i.e. Φ_{room} is constant, and Φ_{sec} may have a distance dependence between these two extremes. A rough estimate is obtained with $\Phi_{\text{sec}} \propto r^{-1}$ which gives

$$Y(n, \gamma) \approx \sigma_0 + a r + b r^2 \quad (5)$$

The influence of secondary neutrons can, thus, be determined by measuring the yield at various distances.

The equation for the distance dependence becomes more complicated for extended sources and samples. Rather than deriving this equation, a Monte Carlo program has been employed to simulate the integration of the neutron flux, $\langle \Phi_0 \rangle$, over the sample. The program was also used to estimate the second term in eq. (4) which accounts for the contribution of secondary neutrons from structural materials. This contribution is relatively small (see below) owing to the design of the target arrangement with little material in the immediate target-sample vicinity. The energy distribution of secondary neutrons and the cross sections used in the calculations are obtained in the same way as those in Section IV A. It is assumed, as above, that the neutron background from room-scattered neutrons does not depend

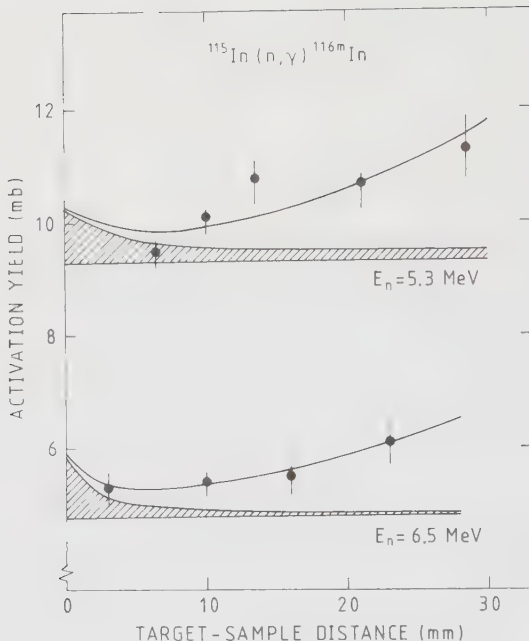


Figure 4 : Activation yield for different source-to-sample distances. Solid deuterium targets were used in the 5.3 MeV measurements and the gas target was used in the 6.5 MeV measurements. The target-sample distance was defined as being the distance from the beam stop to the sample. The dashed curves represent fits made according to the procedure described in the text. Only statistical uncertainties are given.

on the distance (in the target-sample region) so the distance dependence of the third term in eq. (4) comes entirely from the denominator, $\langle \Phi_0 \rangle$. Hence, the magnitude of this contribution can be determined by fitting the experimental data. The dashed curves in Fig. 4 are fits made using this procedure.

Several measurements were performed to study the influence of secondary neutrons produced in the beam stop, gas-target tube

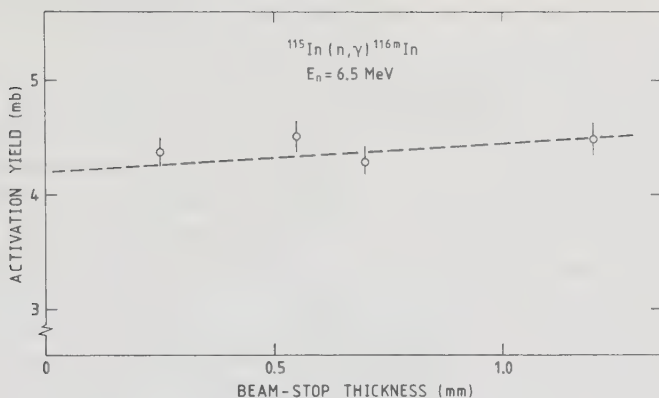


Figure 5 : Activation yield for different thicknesses of the beam stop of the gas cell. The solid line represents the contribution obtained from calculations.

and other structural materials in the target-sample area. As an example, the results of measurements with a gold disc, 1 cm in diameter, placed 5 mm from the beam stop of the gas cell are shown in Fig. 5. The thickness of the disc was varied up to 0.95 mm and the $^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$ activity was measured with the sample 15 mm from the beam stop. The solid line in the figure represents the calculated dependence of the activation yield on the beam-stop thickness. From the results it was concluded that the contribution to the activation yield of secondary neutrons from the structural material was 0.20 mb at a distance of 10 mm from the gas cell (with a 0.45 mm thick beam stop).

C Energy dependence.

From the results presented above some general conclusions can be drawn concerning the background from secondary neutrons. We consider first the contribution to the activation yield from

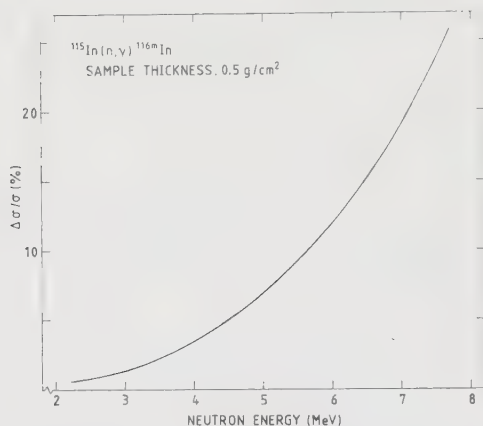


Figure 6 : The contribution to the activation yield from secondary neutrons produced in the sample, $\Delta\sigma$, in percent of the true cross section, σ , as a function of neutron energy.

secondary neutrons produced in the sample itself. The results in Fig. 3 indicate that the background yield is essentially independent of the primary-neutron energy in the region studied in this work. Moreover, the model calculations predict that the contribution of secondary neutrons is nearly constant with energy from about 2.5 MeV up to the (n,2n) threshold at 9.0 MeV for ^{115}In . This comes about because $\sigma(n,n')$ varies only slightly with energy and, furthermore, $I(E)$ is rather insensitive to the primary neutron energy.

We found it remarkable that the magnitude of the correction for the room-scattered neutrons depends so strongly on the location off the target in the room. The new target location, about 2.5 m from the walls of the room, gives significantly lower background than the previous location. For a given location, the correction is approximately constant with the neutron energy and also

independent of the target type used.

Thus, our results show that for measurements performed with one and the same target arrangement, located at the same place, the total contribution from secondary neutrons can be considered to be independent of the primary-neutron energy between 2.0 and 7.7 MeV. The capture cross sections for ^{115}In and ^{197}Au , on the other hand, drop rapidly with neutron (see Section V). Hence, the correction due to secondary neutrons will become more important as the neutron energy increases. Fig. 6 shows the contribution from the background produced in the sample itself in percent of the true cross section for the ^{115}In measurements as a function of neutron energy. The indium sample under consideration was 0.5 g/cm^2 thick (typical for the ^{115}In measurements) giving a contribution of 0.6 mb. As can be seen in the figure the correction is less than 10% for energies below approximately 5.2 MeV. For the highest neutron energies used in this work the correction is about 25%.

V CAPTURE CROSS-SECTION MEASUREMENTS

The neutron-capture cross sections were determined for the nuclei ^{115}In and ^{197}Au in the energy range 2.0 - 7.7 MeV relative to the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ cross section which was taken from [3]. The cross section results are summarized in Table II and in Figs. 7 and 8. The cross sections in the energy region 2.0 - 2.5 MeV, previously reported with relatively large uncertainties [1], have been remeasured with significantly improved accuracy. The results for energies 2.6 - 4.5 MeV are from our previous work. The average neutron energy of the primary neutrons hitting the sample was calculated with a computer program NENINA [10], which takes into account the projectile-energy degradation in the target and the variation of the neutron intensity and energy with emission angle. The full

width at half maximum (FWHM) of the energy distribution is typically 100 keV [1].

The cross sections have been corrected for the contribution of secondary neutrons by using the measured dependences on the target-sample distance and the sample thickness. The thickness corrections were obtained by linearly extrapolating the yield curve to zero thickness. The contribution from sources outside the sample was assessed by fitting the experimental data to the calculated distance dependence of the yield (see Section IV B). Corrections were also made for the contribution from charged-particle reactions in the target as explained in Section III.

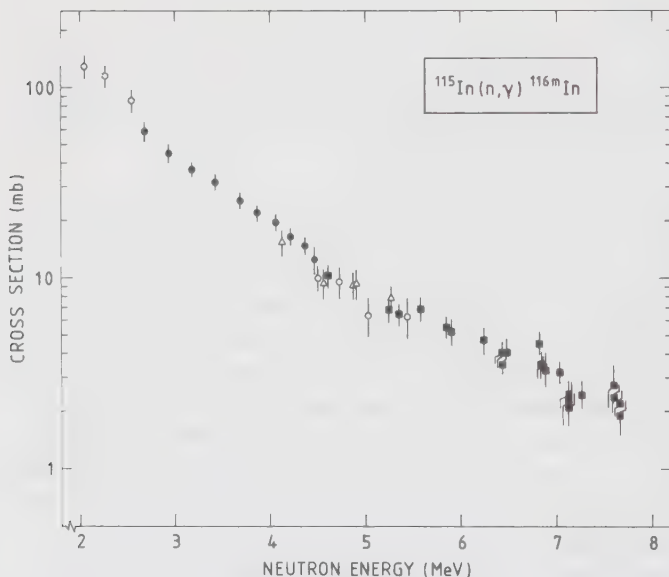


Figure 7 : Cross section for the reaction $^{115}\text{In}(n,\gamma)^{116m}\text{In}$ as a function of neutron energy. The different target types used in the measurements are $\circ$ $T(^{90}\text{Zr}+\text{Au})$, $\bullet$ $T(\text{Ti}_{\text{nat}}+\text{Al})$, Δ $D(\text{Zr}_{\text{nat}}+\text{Au})$ and $\blacksquare$ gas target.

The correction for secondary neutrons produced inside the sample may be too small. According to the model calculations, the dependence of the activation yield on sample thickness is not linear for small thicknesses (see Fig. 3). A linear extrapolation to zero thickness would then give too small a correction. We have not taken this non-linearity into consideration since it could not be experimentally verified, with the present arrangement, whether the effect is real or due to shortcomings of the model. Taking the effect into account, however, would lower the ^{115}In cross sections by 0.5 mb and the ^{197}Au cross sections by 0.3 mb. Thus, the effect would be significant in the higher-energy region and must be further studied.

The different types of targets used in the measurements are indicated by different symbols in the two figures. As has been pointed out in previous sections, the background problems differ considerably for the different target types. For instance, at $E_n \approx 5.0\text{--}5.5$ MeV the signal-to-background ratio for the gas target is about eight times better than for the solid $\text{D}(\text{Zr}_{\text{nat}} + \text{Au})$ targets. In spite of this large variation in the experimental conditions, there is excellent agreement in the cross-section results in the energy regions for which more than one target type was used, indicating that the background contributions have been properly corrected for.

The error bars reflect uncertainties coming from several sources. The statistical uncertainty (typically 3-14%) contains the contribution from the primary-neutron yield measurements as well as the uncertainty in the empty-target yield determination. The cross section of the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ reference reaction has been determined [3] with an accuracy of $\pm(6\text{--}10\%)$. Other

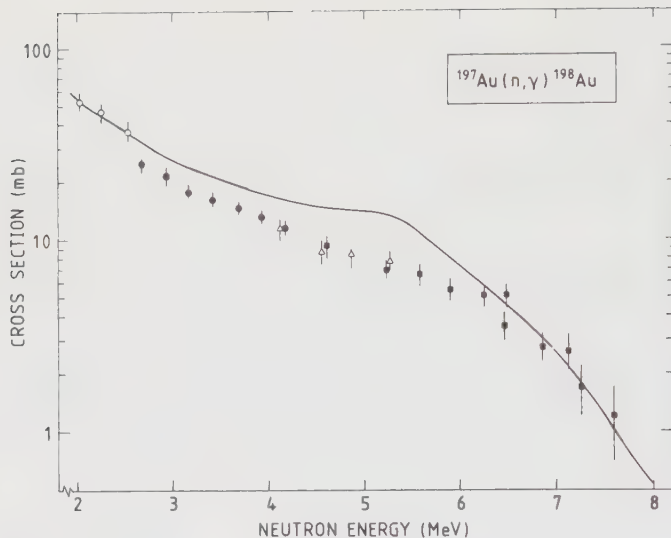


Figure 8 : Cross section for the reaction $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ as a function of neutron energy. The solid curve represents the ENDF/B-V evaluation [14]. The different target types used in the measurements are $\circ$ $T(^{90}\text{Zr}+\text{Au})$, $\bullet$ $T(\text{Ti}_{\text{nat}}+\text{Al})$, Δ $D(\text{Zr}_{\text{nat}}+\text{Au})$ and $\blacksquare$ gas target.

contributions are related to uncertainties in the relative detection efficiency (2%), the γ -ray correction factors (1-3%) and the half lives and branching ratios (1-3%). The correction for secondary neutrons, produced both inside and outside the sample, was typically 1 mb and was determined with an accuracy of about ± 0.4 mb. This uncertainty gives a small contribution to the total uncertainty at lower energies but becomes of major importance at higher energies. The total uncertainties amount to typically 10-20% both for the ^{115}In and the ^{197}Au cross sections.

The cross-section results from the present work are not compared here with results from other measurements. Instead it is our intention to present a detailed discussion together with results

of theoretical calculations in a future publication.

ACKNOWLEDGEMENTS

We are very grateful for the considerable technical assistance of C. Nilsson and K. Håkansson and we would also like to thank Dr D.M. Drake for helpful discussions.

TABLE I. Decay data for the γ rays utilized in the present work.

REACTION	ENERGY (keV)	HALF-LIFE (s)	INTENSITY ^a (%)	REF
$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$	1293.54	3247 $\pm$ 3	85 $\pm$ 2	[11][12]
$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	336.0	16150 $\pm$ 14	45.9 $\pm$ 0.3	[13]
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	411.80	232848 $\pm$ 173	95.55 $\pm$ 0.08	[13]

a) Photons per 100 decays of the reaction product nucleus.

TABLE II. The present capture cross section results and data for the reference reaction [3].

	$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$		$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$		$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	
E (MeV)	σ (mb)	$\Delta\sigma$	σ (mb)	$\Delta\sigma$	σ (mb)	$\Delta\sigma$
2.03	130	17	53	6	264	26
2.26	116	15	46	5	309	31
2.54	85	12	37	5	331	33
2.68	59	7	25.3	2.9	336	34
2.93	45	5	21.7	2.4	334	33
3.17	37	4	17.8	1.6	332	27
3.42	32	3	16.3	1.5	331	26
3.68	25.5	2.5	-	-	328	"
3.69	-	-	14.8	1.3	"	"
3.86	22.0	2.2	-	-	322	"
3.93	-	-	13.2	1.2	320	"
4.06	19.6	2.0	-	-	315	25
4.13	15.4	2.4	11.5	1.6	313	"
4.18	-	-	11.6	1.1	312	"
4.21	16.5	1.7	-	-	311	"
4.36	14.7	1.5	-	-	310	"
4.46	12.5	2.1	-	-	311	"
4.50	10.0	1.1	-	-	"	"
4.56	9.5	1.7	8.7	1.3	312	"
4.61	10.3	1.5	9.3	1.3	312	"
4.73	9.6	1.5	-	-	315	"
4.87	9.2	1.5	8.5	1.5	317	"
4.90	9.4	1.7	-	-	318	"
5.03	6.4	1.6	-	-	321	26
5.24	6.8	1.0	7.0	0.9	327	"
5.27	7.9	1.0	7.8	0.9	328	"
5.35	6.5	0.8	-	-	330	"
5.42	6.3	1.7	-	-	333	27
5.58	6.9	1.0	6.6	0.9	335	"
5.85	5.6	0.8	-	-	338	"
5.90	5.2	0.9	5.5	0.8	338	"
6.25	4.8	0.8	5.1	0.7	339	20
6.43	3.6	0.5	-	-	335	"
"	4.1	0.5	-	-	"	"
6.47	4.1	0.5	3.6	0.6	334	"
6.49	-	-	5.2	0.6	333	"
6.82	4.6	0.6	-	-	316	19
6.84	3.6	0.6	-	-	315	"
6.86	3.4	0.4	2.8	0.5	314	"
"	3.4	0.7	-	-	"	"
7.03	3.2	0.4	-	-	306	18
7.13	2.5	0.4	2.6	0.5	301	"
"	2.1	0.4	-	-	"	"
"	2.3	0.6	-	-	"	"
7.26	2.5	0.4	1.7	0.5	298	"
7.60	2.4	0.4	1.2	0.5	295	"
"	2.8	0.7	-	-	"	"
7.66	1.9	0.4	-	-	296	"
"	2.2	0.4	-	-	"	"

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